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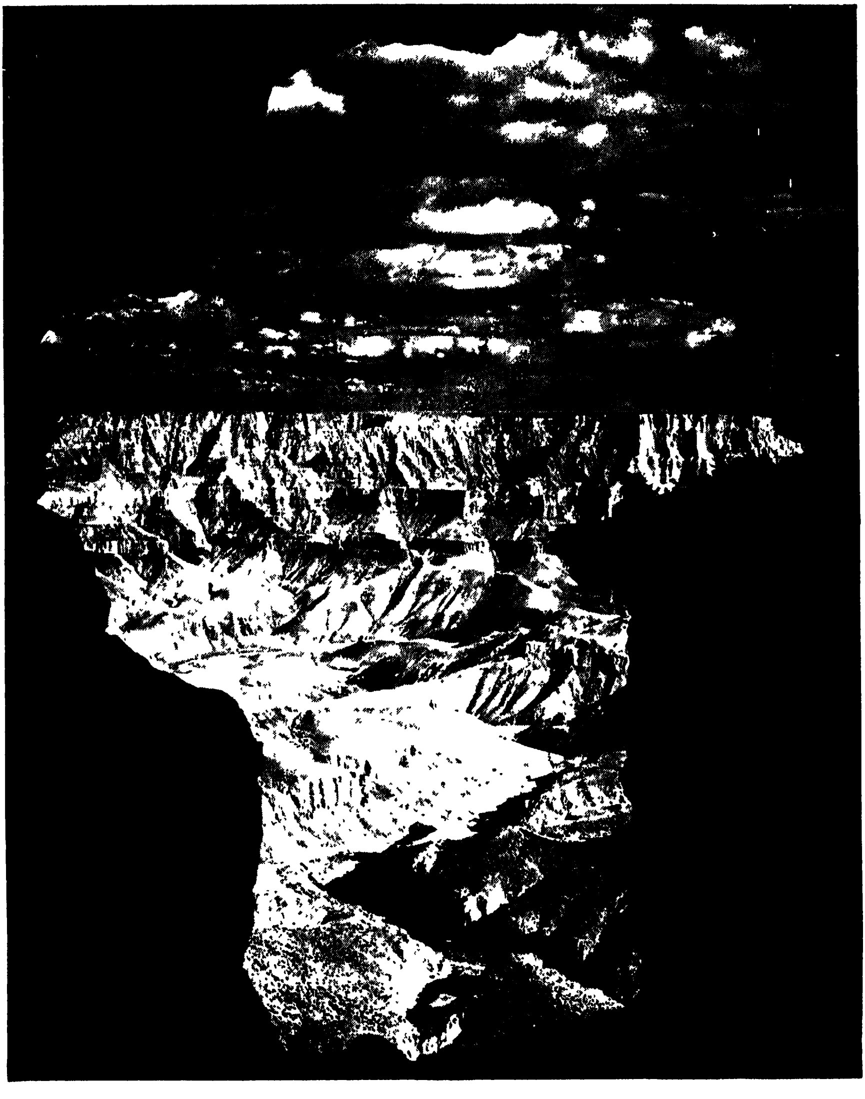
GEOLOGY AND MAN



Grand Canyon National Park (north rim). The surface is the Kaibab Plateau. Exposed on the walls of the canyon are (going down) the flat-lying younger sedimentary formations, an angular unconformity, and the tilted and beveled older rocks. *Courtesy Union Pacific Railroad.*

GEOLOGY AND MAN

by Kenneth K. Landes
Professor and Chairman,
Department of Geology
University of Michigan, Ann Arbor

and Russell C. Hussey
Professor, Department of Geology
University of Michigan

Englewood Cliffs, N. J.
PRENTICE-HALL, INC.

PRENTICE-HALL GEOLOGY SERIES

Norman E. A. Hinds, Editor

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Englewood Cliffs, N. J.

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FIRST PRINTING . . . . OCTOBER 1948
SECOND PRINTING . . . JANUARY 1949
THIRD PRINTING . . SEPTEMBER 1949
FOURTH PRINTING . . . . APRIL 1953
FIFTH PRINTING . . . . . JUNE 1954
SIXTH PRINTING . . . . . JUNE 1956
SEVENTH PRINTING . . . JUNE 1957

Printed in the United States of America

35238

Preface

Geology and Man is designed for a one-term course which may be both a beginning and a terminal course in Geology. This edition contains four chapters on Historical Geology of which three: The Study of Earth History, The History of Life on Earth, and The Geologic Story of the Earth were written by Professor Russell C. Hussey. The chapters on Historical Geology are not included in the briefer *Physical Geology and Man,* an edition intended for use during the first term of a two-term course in Physical and Historical Geology. The authors have attempted particularly to emphasize the effects that geologic processes, acting both in the past and in the present, have had upon mankind. Therefore, this book includes not only a study of the geology of various mineral resources and an analysis of physiography's controlling influence on man's activities, but it also provides longer than usual accounts of the effects of such catastrophic geologic agents as floods, hurricanes, volcanic explosions, and earthquakes.

A logical, though rather unorthodox procedure, is the inclusion of a separate chapter, Direct Action of Gravity, which describes and analyzes the various kinds of mass movements and topographic features produced mainly by gravity. Ordinarily, books on geology cover this topic in a chapter on ground water, even though ground water had little or nothing to do with their origin or development.

Little attempt has been made to give students an acquaintanceship with minerals by means of the written word, because these fundamental units in the architecture of the earth's crust must be seen and handled. If no provision is made for laboratory exercises or field work, the instructor should at least provide specimens of the common rock-forming minerals and of the most abundant ore-minerals, and call the students' attention to the diagnostic properties of each.

During the period that this book has been in preparation (several years), many people have given generously of their time to read the manuscript critically or to locate suitable illustrations. To each of the following: the late Kate Stevens, Jane Plummer, R. C. Moore, R. M. Dreyer, W. H. Schoewe, H. T. U. Smith, J. Hoover Mackin, Kirk Bryan, J. T. Wilson, M. W. Senstius.

Claude Hibbard, T. S. Lovering, A. J. Eardley, Helen Foster, G. M. Stanley, and N. E. A. Hinds, and especially to Susan Beach Landes, we owe much for helpful criticism and suggestions. An acknowledgment is made with each illustration, but in addition to these terse credit lines we wish to recognize here the highly valuable contribution of each donor. An unusual number of excellent photographs were given by M. V. Denny of the Department of Mineralogy, University of Michigan, and by the Union Pacific Railroad. John Jesse Hayes not only made the drawings but also served as illustrations editor for the entire text.

KENNETH K. LANDES

RUSSELL C. HUSSEY

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PART ONE

Introduction

CHAPTER 1

The Science of Geology

THE LITERAL DEFINITION OF GEOLOGY IS "earth science." It is a history of the earth and of its plant and animal life. It includes a study of all earth materials and the forces and processes which have affected them during the long course of earth history.

Relationship between geology and other sciences. The division of knowledge into separate subjects is largely an arbitrary procedure, for there are no fixed boundaries between the various fields of thought. Geology merges in various directions with other sciences. The origin of the earth, for example, is a phase of geological study, but the origin of the various members of the solar system, which includes the earth, lies in the field of astronomy. The materials composing the earth are chemical elements and compounds, and the science of inorganic chemistry had its beginnings in the study of the composition of minerals. The geological forces acting within, and at the surface of, the earth follow physical laws, and the analysis of the mechanics of these processes overlaps the field of physics. The study of the past inhabitants of the earth is a branch both of biology and geology. The study of man and his epoch of earth history is carried on by geologists, anthropologists, and ethnologists, and the final chapter in the geological past includes subject matter considered in the field of human history. The geologist engaged in the exploitation of mineral deposits finds that the laws of economics determine whether or not the deposits are of commercial value.

Divisions of geology. Geology, like the other sciences, has been divided into various fields, and most geologists are specialists in one or more subdivisions. The physical geologist, or physiographer, investigates the work done on or near the surface of the earth by wind, water, ice, and other agents. The rocks of the earth's crust are examined by petrographers; the minerals within the rocks by mineralogists. The study of the origin and early stages of the earth, and of the relationship between the earth and the rest of the solar system, is the work of the cosmogonist. Earth history since the beginning of the rock record is studied by the stratigrapher, a specialist in deciphering the record, and by the paleontologist, who traces the evolution of life upon the earth by means of fossils buried in the rocks. The application of geology to the search for valuable minerals, and to other practical activities, is the field of the economic geologist.

History of geology. The history of geology, like that of other branches of learning, deals mainly with contributions made to the science by various individuals through the centuries, and also with controversial questions about which thinkers argued vehemently, in some cases for decades, before the weight of evidence caused the general acceptance of one idea and the abandonment of opposing views.

The older philosophers were "catastrophists," believing that such land forms as canyons were formed by a sudden yawning apart of the earth's crust. This method of reasoning was quite natural, for the early thinkers lived in the Mediterranean area where two catastrophic geologic phenomena, earthquakes and volcanoes, were well known.

Modern geologists subscribe to the doctrine of "uniformitarianism." According to this belief, the geologic agents now in operation, such as rivers, winds, and ocean waves, have been active in the past and have been mainly responsible for the sculpturing of our present topography. The acceptance of this doctrine necessitated a great increase in our concept of the length of geologic time, which subsequently was verified by determinations of the age of certain minerals through methods recently developed.

Although the doctrine of uniformitarianism is now generally accepted, we realize that the activity of some of the geologic processes operating at the surface today is greater than the average during the past. Since the continents now stand at a higher average elevation than they did during the greater part of the past, agents like gravity and running water, the most important of the geologic agents, are working at a higher than average rate today because of the abundance of steep slopes.

The beginnings of geologic thought no doubt extend far back into antiquity, but for this early period there is no record other than myths and legends. From their writings, we know that some of the early philosophers of Greece and Rome observed contemporary geologic phenomena and, in some instances, made conjectures about the activity of geologic processes in the past. Aristotle considered that earthquakes and volcanoes were closely connected and were due to movements of wind within the earth; he believed that the escape of the wind produced the volcanic eruptions. Seneca held that volcanic eruptions occurred when wind met sulphur and other combustible materials, which were ignited by friction. Herodotus noted the great load of silt carried by the river Nile and concluded that "Egypt is the gift of the river"; he recognized that part of Egypt is land made by the seaward building of the Nile delta. Fossils of sea shells, embedded in rocks high above the level of the Mediterranean, were observed by many philosophers of old and their true origin appreciated.

During the Dark Ages the development of geology, along with that of other branches of learning, was seriously retarded. For example, over a considerable period of time, fossils found above the sea were thought to be either freaks of nature or proofs of the Noachian deluge. Leonardo da Vinci (1452-1519), Italian painter, engineer, inventor, and scientist, was one of the first to recognize their true origin. About 150 years later, Nicholas Steno (1631-1687), a Catholic churchman, published the first paper in which any attempt was made to decipher the history of the earth from the fossils contained in the rocks. Here was the foundation for the *science* of geology.

At about the same time René Descartes (1596-1650) in France, was contributing the first acceptable ideas as to the origins of the earth and of the other planets. He believed that the earth was formed through the cooling of an originally hot gaseous mass like the sun, resulting in the solidification of an outer shell over a still-hot core. France also produced Lamarck (1744-1829), who was the founder of invertebrate paleontology and one of the originators of the doctrine of evolution.

A German, Abraham Gottlob Werner (1749-1815), greatly influenced geologic doctrine for several decades. He was a great teacher, and students came to him from many countries. To him modern geology owes the fundamental concept that, in any series of horizontal strata, the higher beds were laid down later than the lower, and in consequence are younger. At the same time, however, Werner thought that practically all rocks, including granite, ore veins, and even lavas, were precipitates from a universal sea. He was not a traveller, and consequently his reasoning did not have the benefit of the observation of volcanoes. Geologists of wider experience contradicted Werner in this regard, and a controversy waged for many years between Werner's supporters, who were known as "Neptunists," and the "Volcanists," who believed that lava, granite, and cer-

Fig. 1. Sir Charles Lyell (1797-1875) who spread the gospel of uniformitarianism.
By John Jesse Hayes.

ain other types of rocks were formed through the cooling and solidi-ication of molten materials.

Geology owes a debt to three Englishmen, Hutton, Playfair, and Lyell (Fig. 1) for originating and spreading the doctrine of uniformitarianism. James Hutton (1726-1797), a Scot, was first a doctor, later an agriculturist, and at all times a keen observer of geologic processes. He is credited with originating the doctrine, but his exposition of it was cumbersome, and it remained for John Playfair (1748-1819) to publish a much more readable account of the "Huttonian Theory," which led to its general acceptance. Sir Charles Lyell (1797-1875), a widely travelled British geologist, published twelve editions of a *Principles of Geology* and six editions of an *Elements of Geology*. The Huttonian doctrines were incorporated in these widely read texts, which carried the message over the world.

Geology has continued to advance through the activity of many men. In the last few decades it has expanded from a purely philosophical science to a professional science as well. Although geology will always be a great philosophy, now, in addition, it aids the engineer in finding safe footing for dams, the miner in finding ore deposits, the industrialist in discovering new reserves of petroleum, and the farmer in developing underground water supplies for irrigation.

It must not be assumed that all questions in geology have been settled and that additional evolution of thought in the subject is not possible. Geology is a living, growing science, and many of its problems remain to be solved. As old controversies are settled, new ones take their place. The ensuing decades may not see many notable changes made in the branches of geology concerned with the processes that act at the surface and therefore are observable in their activities and accomplishments. On the other hand, many geologic phenomena originate deep in the earth's crust, and the hypotheses advanced to explain them are based largely or entirely upon indirect evidence. New discoveries and new interpretations of evidence will lead to new explanations in the future as in the past. The geology taught one hundred years hence will no doubt differ in many respects from that which we learn today.

Geology and man. The science of geology is being used to an increasing extent by people dwelling in civilized countries, and by no means all of this utilization is commercial in character. A knowledge of geologic forces and products leads to a greater enjoyment of one's surroundings. Most of our national parks and monuments exhibit a host of geologic features, and for this reason the National Park Service employs geologists to show them to the thousands of visitors. However, a knowledge of geology can be applied not only in the regions of magnificent scenery. Any physical environment, no matter how monotonous it may appear to the uninitiated, takes on new interest when its geological origin is understood.

Geology is now used extensively as a means of increasing economic wealth in the search for (1) underground water, (2) mineral fuels, including coal, oil and gas, (3) various other non-metallic minerals, such as road materials, clay, sulphur, and gem stones, and (4) deposits of metals. The largest group of professional geologists is employed in searching for oil and gas; every important oil company has a geologic staff, and most of the discoveries of oil and gas being made today are based on the scientific work of these carefully trained observers.

Another practical use of geology is in engineering projects such as the construction of reservoirs and dams, the curbing of soil erosion, and many others. The practical applications of geology are considered in some detail in the last two chapters.

Methods of geologic investigation. Geology is essentially a field subject, for the history of the earth during the last thousand million years has been deciphered chiefly by the field studies of many geologists. One important product of these investigations is the geologic map which shows, in addition to roads, communities, drainage, and other data found on ordinary maps, the distribution of the various ages and types of rocks at the surface (or just beneath the soil cover). These maps not only contribute to the accumulation of geologic knowledge, but also are of great practical value in the search for valuable mineral deposits.

In many areas, actual rock outcrops are few and widely spaced. Hence, the layman is more or less mystified as to how a geologist can construct a map showing the character of the bed rock at every point. The geologist first collects all available information regarding scattered rock exposures, and then interpolates where information is lacking. He visits all outcrops and makes observations as to the position and elevation of the outcrops, the kinds and ages of the rock formations exposed, the arrangement of the various rock bodies composing the outcrop, the relationship between the different rocks, and the possible occurrence of mineral resources. The outcrops may be natural exposures along the banks of streams and the flanks of hills, or they may be artificial, as are railroad and highway cuts, rock quarries, and other excavations. Even where the rock itself is covered with soil, the distribution of the bed rock formations can be accurately mapped under some circumstances. The position of a rock that is either less resistant or more resistant to erosion than the surrounding rocks commonly is shown by a prominent break in topography. Gopher holes and ant hills yield many clues as to the type of underlying material; vegetation often differs noticeably on opposite sides of a hidden contact between two rock formations.

Geological information regarding more deeply buried rocks may be available from records of mines and drilled wells. Geologists can investigate the rocks exposed in mine workings; the rocks penetrated by drilled wells are studied by means of "cuttings" made by the drill bit and by "cores" obtained by a special type of drill. Data concerning the deeper rocks can be secured also by geophysical instruments such as the seismograph, which makes a record of natural earthquakes or artificially developed vibrations.

In his laboratory, the geologist gives further study to the specimens collected in the field. He examines extremely thin slices of rocks and fossils under the microscope. He may make a variety of physical and chemical tests, in addition to visual and microscopic examinations. By various techniques, fossils, minerals, and rocks are identified, and mutual relationships are noted.

CHAPTER 2

Earth Materials

BEFORE STUDYING THE GEOLOGIC FORCES and agents, we must know about the materials of the earth on which the forces and agents act. Earth materials themselves are the results of geologic processes, and their origins will be discussed in later chapters. We are now concerned solely with knowing what they are and where they occur.

INGREDIENTS OF THE EARTH

Atoms. The atom is the fundamental unit in the composition of matter. It is so small that it remains invisible under even the highest-powered microscopes. In fact, the smallest visible particle of any substance contains millions of atoms.

Investigations by physicists during the last few decades have shown that the atom itself is not a single body but consists of a nucleus around which revolve one or more minute particles known as electrons. The relationship between the electrons and the nucleus has been likened to that of the solar system, in which the relatively small planets revolve about a central nucleus, the sun.

Elements. All matter, whether it be the air we breathe, the water we drink, the food we eat, the clothes we wear, or the ground we walk upon, is composed of chemical *elements.* An element is a form of matter which cannot be decomposed by ordinary physical or chemical experiments. There are 95 elements, of which number over half are so rare that the average individual never hears of them. Some elements, such as iron, copper, lead, zinc, and gold, can be seen and are well known. Others, such as oxygen, occur in gaseous form only. Few elements are known in uncombined form; most of them join with other elements to form a great variety of natural chemical compounds. An example is silicon, which does not occur alone in nature, but, because of its abundance in the common rock-forming minerals, composes over a fourth of the earth's crust.

The accompanying diagram shows graphically the relative abundance of the eight principal elements which compose more than 98 per cent of the earth's crust. The remaining 87 elements account for but 1.37 per cent which is less than the percentage of magnesium, the least abundant element of the first eight. Only two common metals, aluminum and iron, appear among the principal elements. Copper, lead, zinc, tin, and the precious metals are included in the relatively insignificant eighty-seven.

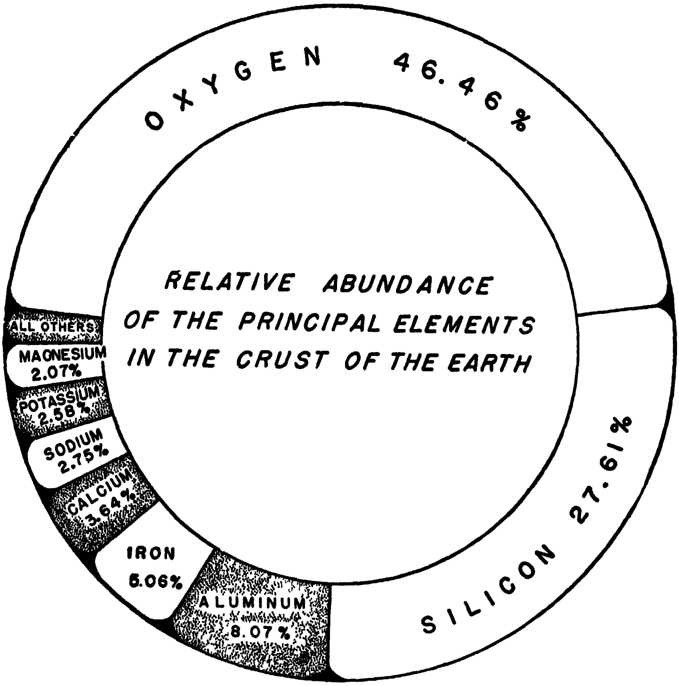

Fig. 2.

Elements have the property of combining in definite proportions with other elements to form *compounds.* Every compound has characteristic physical and chemical properties. Compounds are thus distinguished from *mixtures,* in which two or more substances are mixed together without losing their separate identities. Air is a gaseous mixture of both elements and compounds; water is a simple compound (H_2O) in which the ratio of hydrogen atoms to oxygen atoms is 2 to 1.

Minerals. A mineral is a natural homogeneous substance of definite chemical composition and inorganic origin. Most minerals are compounds of two or more elements, but a few, such as sulphur and native gold, are single elements. Coal and petroleum are not minerals, because they are organic in origin; they are, however, referred to as "mineral fuels" and are included under the broad term "mineral resources."

Most minerals originate through *precipitation* from a solution. The solutions that have yielded the great bulk of minerals have been masses of hot liquid rock, called *magmas.* When a magma cools the compounds in solution crystallize into various minerals. Closely related in origin are minerals precipitated from hot water solutions that have escaped from a crystallizing magma. As the solutions move upward and outward from the magma they become cooler, and precipitation takes place. Mineral veins containing economically important deposits of gold, silver, copper, lead, zinc, and other metals are so formed. Large bodies of water on the earth's surface contain mineral matter in solution, and evaporation of the water beyond the saturation point of the dissolved solids results in their precipitation. The great beds of salt found in various parts of the world today were formed by the evaporation of ancient seas and lakes.

Not all minerals result from precipitation from cooling or evaporating solutions. At and near the earth's surface, minerals are formed by *chemical reactions* between the atmosphere or ground waters and the minerals of rocks with which they come in contact. A relatively insignificant volume of minerals is formed by *sublimation,* when volcanic vapors come into contact with cooler rocks.

When a mineral is formed, its component atoms, with but few exceptions, are arranged in a definite and distinctive pattern. The existence of this pattern was assumed for many years from studies of the behavior of light passing through thin slices—or sections—of minerals. The development of techniques whereby X-rays are transmitted through or reflected from the atomic pattern, or "lattices," has proved their existence. If sufficient space is available when a mineral is formed, the regularity of internal atomic arrangement manifests itself in the development of an external crystal form composed of a series of faces having definite geometrical patterns such as squares and triangles. Consequently, minerals occur either in irregular grains and masses (Fig. 3), partially developed crystals, or com-

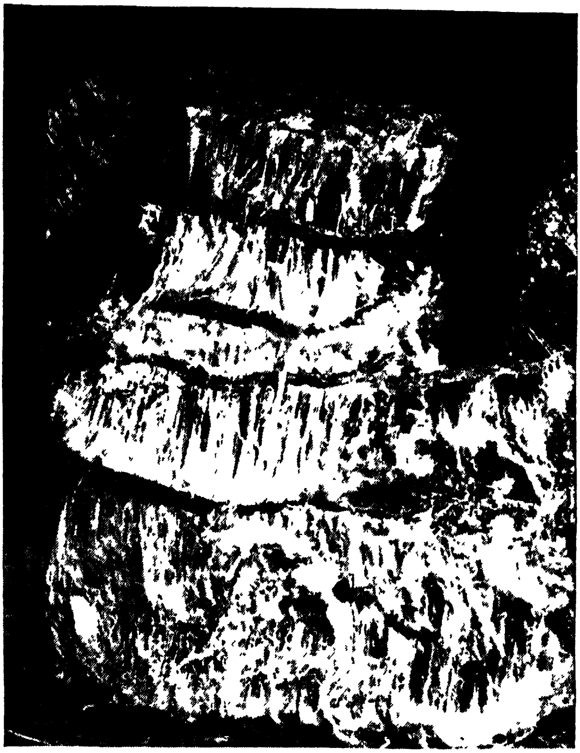

Fig. 3. Asbestos, an unusual mineral that can be woven into fireproof cloth. Crude fibre as it came from the Jeffrey Mine, Asbestos, Quebec. *Courtesy Canadian Johns-Manville Company, Limited.*

plete crystals, depending upon the space available for growth at the time of formation.

The composition of minerals ranges from single elements to complex compounds containing ten or more elements. Chemically, minerals can be classified into various groups, including (1) the elements, such as gold, copper, and diamond, (2) the sulphides, such as galena (lead sulphide), and pyrite (iron sulphide), arsenides, and related compounds, (3) the oxides and hydroxides, which include quartz and bauxite (aluminum ore), (4) the haloids (halogen compounds) such as sodium chloride (salt), and (5) the oxygen salts, such as nitrates, carbonates, sulphates, tungstates, borates, phosphates, and silicates. Of the approximately 1500 mineral species known, about one-fourth are silicates (minerals containing silicon and oxygen in various combinations with other elements), and one family of silicates, the feldspars, makes up about 60 per cent of the known earth's crust. Quartz (an oxide of silicon) and the feldspars, along with other silicates called pyroxenes, amphiboles, and micas, constitute about 87 per cent of the earth's outer shell.

It is also possible to classify minerals by occurrence and utilization. Major groupings in such a scheme are (1) the rock-forming minerals and (2) the ore minerals. The first group consists mainly of silicates and one oxide, quartz. The dominant constituent of limestone, one of the common rocks of the outer earth, however, is calcite, a carbonate of lime. Ore minerals are those from which the metals of commerce and industry are obtained. Examples are native gold and copper, which are single elements; many sulphides, such as chalcopyrite, the leading ore of copper, and hematite, an iron oxide from which most of the world's iron is obtained; malachite, a copper carbonate; and calamine, a zinc silicate. Although ore minerals occur in all of the chemical groups, most metals are obtained from sulphide deposits. Notable exceptions are the chief ore minerals of iron and tin, which are oxides.

Minerals play an important role both geologically and industrially. They are essential constituents of almost all rocks that we see in the outer part of the earth. They undergo changes when acted upon by geologic forces and agents.

Minerals are sources of wealth. Many individuals, communities, and even countries obtain the major share of their incomes through the exploitation of mineral deposits. Throughout history, many wars of conquest have been fought to obtain coveted mineral resources in which the aggressor nation was deficient.

Minerals are sought by collectors and are displayed in museums because of their beautiful color, crystal form, or both. The rarity of many species also excites the interest of the collector. For many centuries, mineral collecting has been a popular hobby.

Rocks. Most rocks are mixtures of minerals; hence they exhibit wide differences in composition and properties. The chemical composition of a rock is not definite as is that of a mineral. One type of rock may grade imperceptibly into another through variation in the proportion of the different minerals present. A few rocks such as limestone, rock salt, and gypsum consist largely or wholly of one mineral. Natural glass, coal, and a few other rocks are not composed of minerals, but these are exceptional.

Rocks are formed, destroyed, and remade by geological processes working through a never-ending cycle. The rocks of the visible part of the earth are divided into three great classes, *igneous, sedimentary,* and *metamorphic.*

Igneous rocks, which compose most of the earth, are formed by the cooling and consolidation of molten liquids. A well known example is *basalt,* a dense, dark rock formed by the "freezing" of a flow of molten lava. However, the most abundant igneous rock is *granite,* which solidifies at moderate depth below the surface. Practically all varieties of igneous rock consist of an aggregate of interlocking crystals. The mineral particles are visible in granite, while in basalt most, if not all, are invisible to the eye. The compact, dense appearance of basalt may be relieved by conspicuous holes through which gas escaped while consolidation was taking place. The holes are especially common at the surface of lava flows.

Sedimentary rocks include such well known varieties as sandstone, limestone, and shale. Most of these rocks are composed of fragments of other rocks and minerals deposited either above or below sea level. Some are composed of organic matter, and others are composed of minerals precipitated from waters. Their chief characteristic is a layering, known as *bedding,* due to the deposition of different types and sizes of particles at different times as the rock was being built up. In most sedimentary rocks, the grains are not interlocking, and, although they may be cemented together by a natural binder, most of the sedimentary rocks are inferior to igneous rocks in hardness and durability. Sedimentary rocks are the only types of rock that contain fossils, evidence of past life.

Metamorphic rocks are igneous or sedimentary rocks which have been subjected to considerable heat and pressure and active subsurface solutions so that the component minerals have recrystallized either into the same minerals or, by internal rearrangement, into different minerals. The new rock is an interlocking aggregate of crystals, as is igneous rock, with comparable hardness and cohesiveness. Recrystallization produces a characteristic banding in some cases and an exceptional rock cleavage in others. Banded rocks include *gneiss* (pronounced *nice*), a coarse-grained rock with the minerals arranged in wide bands, and *schist* (pronounced *shist*), in which the bands are fine. *Slate* is the outstanding example of a cleavable rock. A few metamorphic rocks, such as *marble,* (recrystallized limestone), exhibit neither banding nor cleavage, but merely a coarser crystallization of the mineral or minerals initially present.

In marble, metamorphism has recrystallized the original calcite into a coarse, interlocking aggregate.

DISTRIBUTION OF EARTH MATERIALS

The earth is divisible into three principal parts. The outermost zone is the *atmosphere,* which is composed of elements and compounds in *gaseous state.* The second division is the *hydrosphere,* consisting of *water* which occupies depressions in the surface of the underlying, solid *lithosphere,* which is the third division.

The atmosphere. The atmosphere, or "vapor sphere," is the mixture of nitrogen, oxygen, water vapor, and carbon dioxide that we commonly refer to as air. It is a relatively thin blanket, held to the earth by the same force (gravity) that keeps us from being whirled off into space. The elements in the atmosphere are essential to life; furthermore no rain could fall without an atmosphere. The chemical and physical activities of the atmosphere as a geologic agent will be discussed in the following chapter.

The hydrosphere. About three fourths of the surface of the earth is covered by the waters of the ocean. Through the ages this water has become contaminated by salt and other compounds in solution in the streams that drain the continental areas.

The oceans play both a passive and an active role in geology. They are the source of most of the rain that falls from clouds in the atmosphere. The oceans effectively screen three-fourths of the surface of the lithosphere from several very active agents of erosion, such as rivers and wind. Waves and currents, however, alter the position and shapes of shore lines. The ocean floor is the great depository for sediment which is carried there by various transporting agencies. Many animals and plants live in the waters of the ocean, and the activities of some of these change the configuration of the sea floor. The work of the ocean is described in Chapter 8.

The lithosphere. The solid part of the earth is a spheroid with a circumference of about 25,000 miles and a diameter of about 8,000 miles. If the oceans were not present, and if we could view the earth from a point in space, we would see that its surface had two distinct levels. One-third of the surface stands about three miles above the remaining two thirds. The higher plateau areas are the *continental platforms,* and the low-lying regions are the *ocean basins.* However, the oceans actually occupy three fourths instead of two thirds of the earth's surface by overflowing their basins and encroaching upon the edges of the continental platforms.

The highest mountains rise about five miles above the general level of the continents, and the deepest depressions on the ocean floor are about four and one-half miles below the average level of the ocean basins. Therefore, the maximum relief (vertical distance between highest and lowest points) of the earth's surface is about twelve and one-half miles. This figure is so insignificant when compared with the 4,000-mile radius of the earth that if the earth were shrunk to the size of a tennis ball, it would be just about as smooth.

Our first-hand knowledge of the materials composing the lithosphere is largely confined to the rocks lying at and near the surface of the continents. The deepest wells that have been drilled into the earth have penetrated only a little more than three miles of crust, the deepest mine less than one mile and a half. Actually, however, because of movements within the earth, rocks that have been buried to depths probably exceeding ten miles have been brought to the surface and are available for study.

It has been estimated that over 75 per cent of the land surface is floored with sedimentary rock, and the remainder with igneous and metamorphic rocks. If the thin mantle of soil present almost everywhere is taken into consideration, the amount of surface where igneous and metamorphic rocks are exposed becomes even less. However, both the soil and the sedimentary rocks form an extremely thin "skin," beneath which all of the rocks are either igneous or metamorphic. The latter types of rock crop out mainly in mountainous regions, in so-called "shield" areas where the veneer of sedimentary rocks has been stripped off by erosion, and where extensive plateaus have been built up through the solidifying of countless flows of lava. In North America the coastal plains, the great lowland area drained by the Mississippi River and its tributaries, and some of the lower mountain ranges, are floored with sedimentary rocks, but the higher mountain ranges, the Columbia River plateau of the Northwest, and the great shield area extending from the Great Lakes to the Arctic, are floored with igneous and metamorphic rocks.

PART TWO

Geologic Processes

We are now ready to consider the geologic agents that are at work on and within the earth, and the results of their activity. The following seven chapters discuss the agents that operate at and close to the earth's surface, such as the atmosphere, ground water, running water, ice, gravity, and waves and currents, and the mode of formation of sedimentary rocks. Vulcanism and diastrophism, processes which, for the most part, operate deeper within the earth but also affect the surface, will be considered in Chapters 10 and 11. . . . . .

CHAPTER 3

Work of the Atmosphere

THE ATMOSPHERE WORKS IN TWO PRINCIPAL ways as a geologic agent. Its more important activity is rock weathering, while its less important but still very significant activity is the work of the wind. Rock weathering is a slow and quiet process, involving little or no movement of material. Winds often are violent and do a great deal of work in a brief space of time. They move enormous volumes of rock fragments. The principal result of rock weathering is to loosen material so that it can be transported by the various agents of erosion—gravity, running water, wind, snow, ice and glaciers, lakes, oceans and various kinds of organisms.

ROCK WEATHERING

Weathering is the destructive effect which the atmosphere and other agents have on the rocks at and near the surface of the earth. The atmosphere consists of about 78 per cent nitrogen, an inactive or inert gas, 21 per cent oxygen, a small but variable percentage of water vapor, and less than 1 per cent carbon dioxide and other gases. Oxygen has the power to unite with a great many chemical elements, a process known as *oxidation,* which goes on extensively at and near the earth's surface. To attack rock minerals chemically, oxygen, and also carbon dioxide, must be dissolved in water. Oxygen and carbon dioxide are absorbed by rain as it falls through the atmosphere, and by water as it filters through the upper soils which commonly are rich in organic matter. Animals and plants produce certain chemical compounds during their lives or during decay after death which are important in rock weathering.

Weathering takes place as far down into the crust as the water can penetrate. The formation of a soil cover does not prevent weathering of the underlying bed rock, for there are abundant openings within the soil to permit air to circulate. Likewise, most sedimentary rocks contain open spaces, such as those between grains of sand in a sandstone, which permit ready penetration by the atmosphere. Most igneous rocks have fewer openings and therefore cannot be so easily penetrated by weathering agents. Weathering of lava, however, is facilitated by the abundant holes in the upper part of flows, formed by escaping gases at the time of solidification. Granites and many other rocks would be fairly impervious were it not for the fact that they are invariably traversed by cracks or fractures, called *joints,* which extend down into the rock for considerable distances and greatly increase the area of rock surface open to attack by the atmosphere (Figs. 4, 5, and 6).

The depth to which active weathering can take place is limited by the position of the *water table,* the upper surface of the underground water. A short distance below the water table, weathering ceases, for such oxygen and carbon dioxide as is dissolved in the percolating water which joins the ground water circulation is soon used up. Of course, *hydration* (the union of chemical elements and compounds with water) can take place, but in most minerals hydration is not possible until after oxidation.

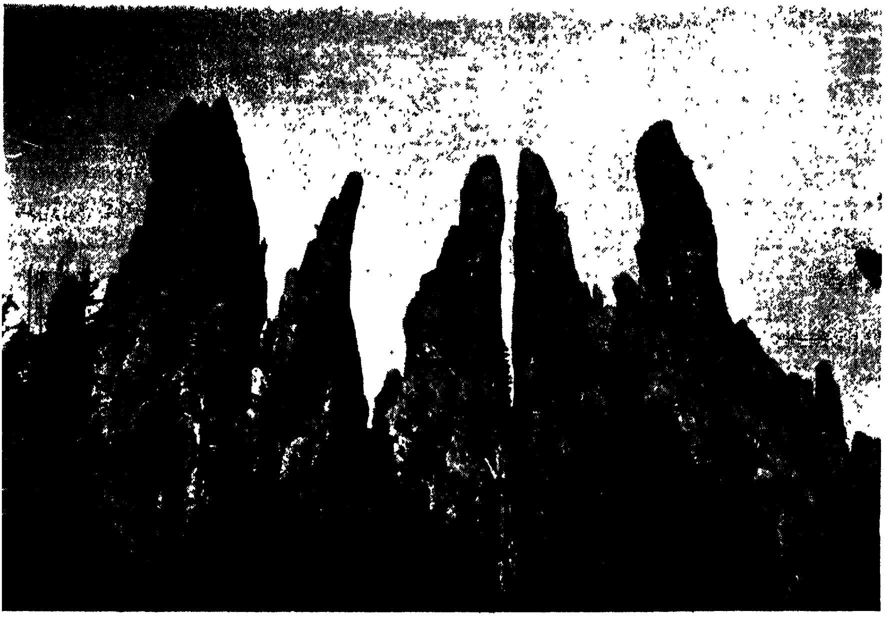

Fig. 4. Granite spires produced by weathering and erosion along vertical joints. The Needles, Black Hills, South Dakota. *By Henry Landes.*

It would be difficult to overemphasize the importance to man of weathering. Without weathering, the surface of the earth would be forbidding indeed. The continents would be surfaced with bare, hard rocks, for no soil cover could be developed; consequently the earth would be devoid of plant and animal life. Fortunately, how-

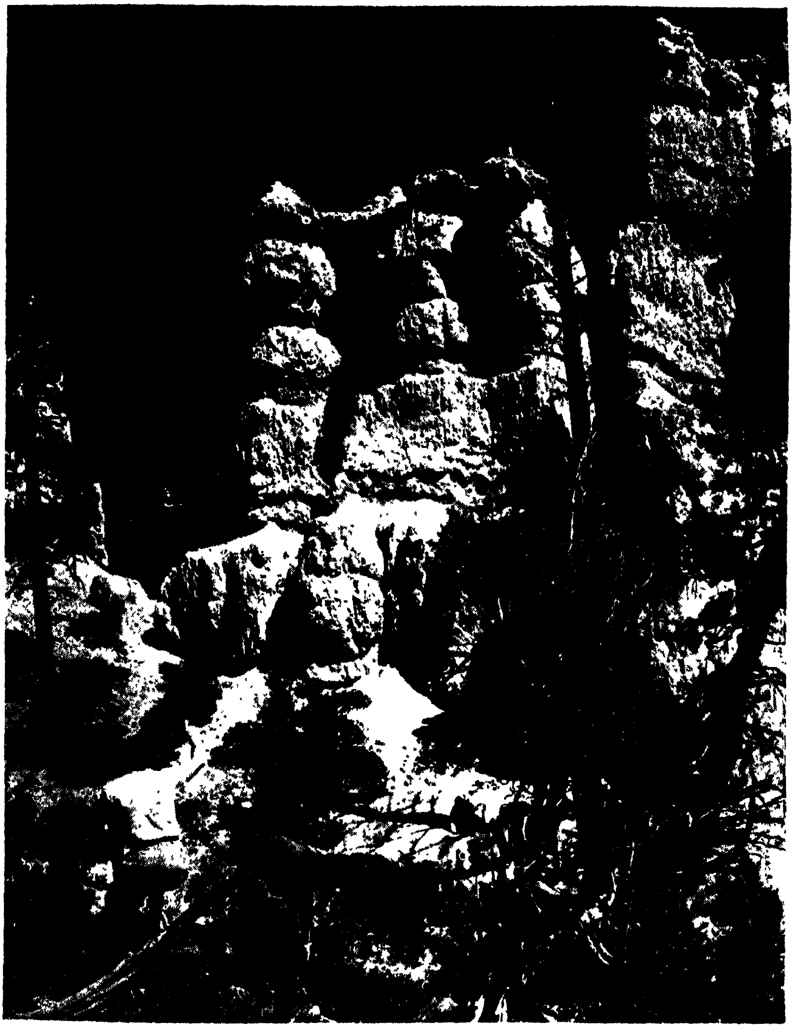

Fig. 5. Turreted spires produced by weathering and erosion along both vertical joints and horizontal layers of sedimentary rock of unequal hardness. Bryce Canyon National Park, Utah. *Courtesy Union Pacific Railroad.*

Fig. 6. Weathering and erosion along joint planes in granite; some of the joint planes are inclined, as shown by the slope of the mountain face to the left. Goatfell, Island of Arran. *Courtesy Geological Survey and Museum, London.*

ever, weathering has been a dominant process throughout known geologic time, hence a soil cover has existed almost everywhere.

The principal geologic function of weathering is to make rock material available for transportation, the first step in the formation of sediment and sedimentary rock. The bed rock is broken into fragments that are movable; and soluble compounds that can be dissolved and removed by surface and underground waters are formed. Besides producing the soil upon which the agricultural and lumbering industries depend, rock weathering has some other very practical results. Sand, gravel, and clay deposits which we use so much are the indirect results of rock weathering. Practically all aluminum ore, most iron ore, and some copper ore have been formed through oxidation and other chemical changes taking place at and near the earth's surface.

WEATHERING PROCESSES

Weathering is accomplished by two methods: physical weathering, which produces disintegration, and chemical weathering, which results in decomposition. In most places, these two processes work together so that the products of weathering result from a combination of activities.

Disintegration. Disintegration is mechanical fragmentation of rock into smaller and smaller units without appreciable change in chemical composition. For example, in many parts of the earth water filling a joint crack in rock at the top of a cliff freezes at night and thaws during the day. Since water expands as it changes to ice, it is capable of producing great pressure on the material enclosing it. In fact, a pressure of about one ton per square inch may be exerted on the surrounding rock. Thus each freezing widens the crack until a block is detached from the cliff (Fig. 7). The same process is repeated in the rock fragments at the foot of the cliff until they also have been split apart many more times. The accumulation of angular rock fragments at the foot of a steep slope is known as "slide rock" or *talus* (Fig. 8).

Plants and animals are important disintegrators of rock. The roots of trees and other plants, growing in joint cracks or other openings in rocks, will force blocks apart. Worms and burrowing animals break up weak rocks.

Decomposition. Chemical weathering results in the *alteration* of minerals. When exposed to atmospheric attack, most minerals alter by uniting with the active elements and compounds (oxygen, carbon dioxide, and water) in the atmosphere. A *primary* (original) mineral alters into one or more *secondary* minerals, which

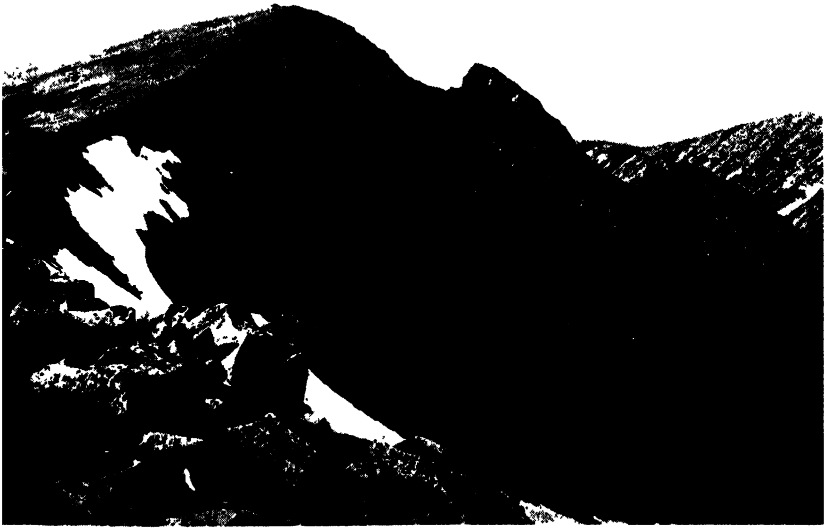

Fig. 7. The action of frost in rock weathering. The large rock fragments in the left foreground, as well as the debris on the slopes, are products of frost wedging. Carn Dearg Meadhonach, a granite mountain near Ben Nevis, Invernesshire. *Courtesy Geological Survey and Museum, London.*

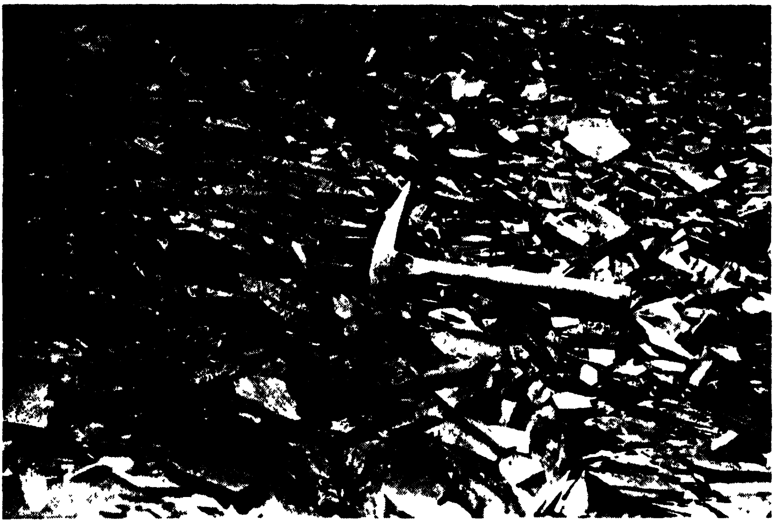

Fig. 8. Talus of disintegrated shale fragments. Cinnamon Mt., Colorado. *By J. W. Vanderwilt. Courtesy Geological Survey, U. S. Department of the Interior.*

are soft and readily transported by wind and water. Chemical weathering also produces soluble compounds which are carried away by surface or underground waters. Chemical changes in minerals are varied and complicated. *Oxidation* is illustrated by the union of iron with atmospheric oxygen to form iron oxide (the mineral hematite). *Carbonation* is the union of elements in a mineral with carbon dioxide from the atmosphere, producing a carbonate. For instance, copper which is exposed to the atmosphere alters to green copper carbonate. *Kaolinization* is a very common process of mineral alteration. When feldspar is altered chemically, carbon dioxide unites with the potassium, sodium, or calcium in the feldspar to form a soluble carbonate which is carried away in solution. At the same time. water unites with aluminum and silica of the feldspar to form kaolin or some other clay mineral. Since feldspar is the most abundant mineral in the outer part of the earth, clay minerals are common at the earth's surface.

The union of water with mineral matter is *hydration;* a common example is the alteration of iron, or iron oxide (hematite), into hydrous iron oxide (limonite). Clay shale exposed at the surface absorbs water and reverts to massive clay, but this is chiefly a physical rather than a chemical hydration.

Chemical processes may cause considerable increase in volume, which assists in the disruption of rocks. For example, the zone of rock next to the surface will be the first to decompose; as it decomposes it expands so that it no longer fits tightly against the underlying rock. This will cause it to "shell off," exposing the fresh rock beneath. The scaling off of successive skins is known as *exfoliation;* it resembles the peeling of an onion.

Solution. Decomposition processes and percolating water work together to produce what is known as solution weathering, or *leaching,* the removal of soluble substances in the rocks at or near the surface. The activity of bacteria accelerates leaching; it has been found by experiment that leaching is 53 per cent more effective when bacteria are present than when conditions are sterile. A few rock-forming minerals, such as calcite, are slowly soluble in percolating water; in such cases decomposition is not a necessary prelude to leaching. The pitted surfaces of outcropping limestones are due to solution weathering of calcite.

The vulnerability of rocks to the chemical work of the atmosphere depends upon several factors, of which the kind of minerals composing the rock is the most important. Rocks composed of feldspar, calcite or iron-magnesium minerals, which are susceptible to decomposition or solution, are less stable than rocks composed of other minerals. The character of the minerals cementing the grains of a sedimentary rock such as a sandstone controls its resistance to disintegration. Some mineral cements, like calcium carbonate, are readily leached; others, like silica, are as resistant to attack as the sedimentary grains of the rock itself. Grain size also is important, for weathering proceeds with greater rapidity in coarser grained varieties of the same rocks. Therefore, a fine-grained, dense granite or limestone is more durable than coarser grained phases of the same rocks. The mutual relationship of the individual grains is a further factor. Interlocking aggregates of crystalline minerals make rocks less vulnerable.

Climate is an important factor in rock weathering; a warm, moist climate accelerates chemical decomposition. Extreme daily and seasonal variations in temperature aid rock disintegration. Thus, the amount and kind of weathering that takes place depends upon the environment of the rocks as well as their composition. It is impossible to list rocks in the order of their resistance to attack by the atmosphere. One rock might be much more durable than another under certain conditions of climate, texture, and structure, but under different conditions their positions might well be reversed. As a general rule, igneous and metamorphic rocks stand up better than sedimentary rocks, but quartzite, a silica-cemented sandstone, is one of the most durable of rocks.

RESULTS OF WEATHERING

Residual mantle. Natural exposures of bed rock are common in some areas, but in most places weathering has broken down the rock so that it is covered by a veneer of loose material. This veneer, or *mantle,* ranges from a few inches to many feet in thickness, depending upon the climate, type of rock, and length of time during which undisturbed weathering has gone on. The composition of the mantle also depends upon these conditions. Rock surfaces in a desert generally are veneered with chips and grains broken from the underlying rock, while in a more humid region there is usually a complete gradation downward from mantle into solid rock. The term *residual mantle* is used to distinguish weathered fragments in place (Fig. 9) from *transported mantle* which consists of loose materials moved from their source. Transported mantle in places blankets the bedrock through thicknesses of hundreds of feet.

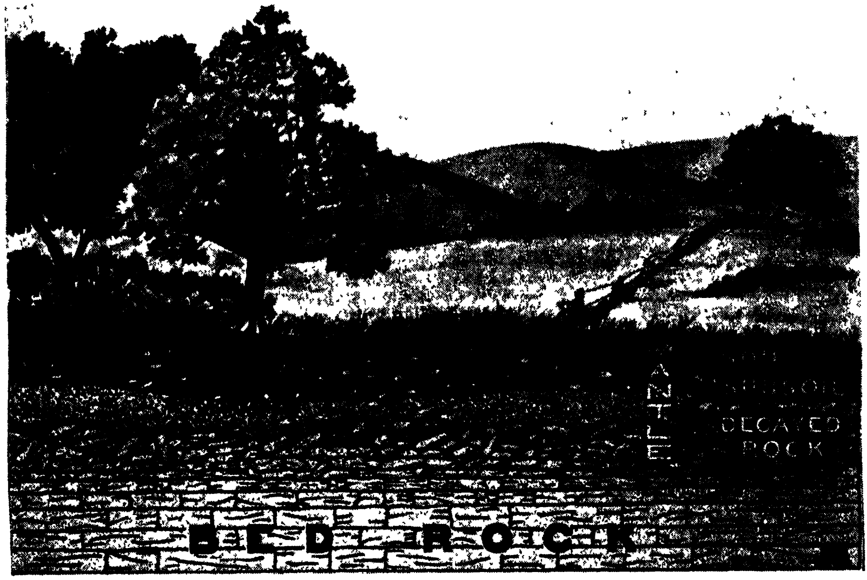

Fig. 9. Relationship between bed rock and residual soil. *By John Jesse Hayes.*

Soil. Soil is that part of the residual or transported rock mantle which supports the growth of plants. It comprises chiefly more or less finely divided, physically and chemically altered rock fragments, together with organic material that has accumulated through the growth and death of many generations of plants.

The character of soil in the early stages of its evolution depends mainly upon the composition of the parent rock. Soil minerals are those which form through oxidation, hydration, carbonation, and leaching of the minerals in the original rock. The extent to which these chemical processes operate is a function of climate, topography, and time. Furthermore, various plants introduce new compounds so that additional chemical reactions take place. Consequently, older, or "mature," soils are dependent in character and composition more upon their environment than upon the composition of the original rock. The same kind of rock may produce totally different soils under different environmental conditions, and conversely, similar environments eventually will produce similar soils from rocks quite unlike in character.

Soils also are produced almost entirely by leaching processes. For example, limestone, composed mainly of calcium carbonate, is relatively soluble and is gradually dissolved by percolating water. The impurities within the limestone, such as grains of sand, particles of clay, and pieces of chert (a white, dense form of quartz), are relatively insoluble and therefore tend to be left behind. In the region bordering the Ozark upland in the states of Missouri and Arkansas, where cherty limestones are abundant, the soil contains large quantities of residual chert. Leaching also will cause the reversion of a sandstone into loose sand by removing the calcium carbonate or limonite cement which has held the sand grains together.

Utilization of soil. Soil is essential to the world's greatest industry, agriculture. Therefore, its character and evolution have been the subject of much study, both by individual scientists and by governmental organizations. Where the mantle rock has not been disturbed, it is possible to identify various layers of soil between the surface and the unaltered bed rock. The soil at the surface is, of course, the oldest of the weathered phases and shows the least similarity to the source rock; and weathered zones below the soil show increasing chemical similarity to the bed rock.

The top soil layer is the one in which activity of organisms has been greatest; hence its fertility is likely to be greater than that of lower zones. Where deforestation, overgrazing, or improper cultivation have exposed the top soil so that it is blown or washed away, there is great economic loss, since it will take many years for nature to make the underlying weathered material equally fertile.

Besides the danger of removal of top soil, the agricultural industry is also faced with decreased fertility of much of the soil because of too-long-continued production of certain types of crops. The chemical changes going on within the soil do not end when the pioneer farmer first plows up the virgin sod. Chemical activity continues, but it is controlled to a considerable extent by the types of crops the farmer plants, and by the methods of tilling he uses. The determination of the best use to which different types of soil can be put and of the proper treatment of soils, have been major contributions of scientific agriculture.

Gossans. The exposure of minerals in an ore deposit to chemical weathering results in the formation of a *gossan*, or capping, of oxidized minerals overlying the unaltered ore body (Fig. 10). A gossan can extend to the depth of the surface of the ground water, or water table. Gossans reach several hundred feet in depth in arid regions and are absent in exceptionally humid localities.

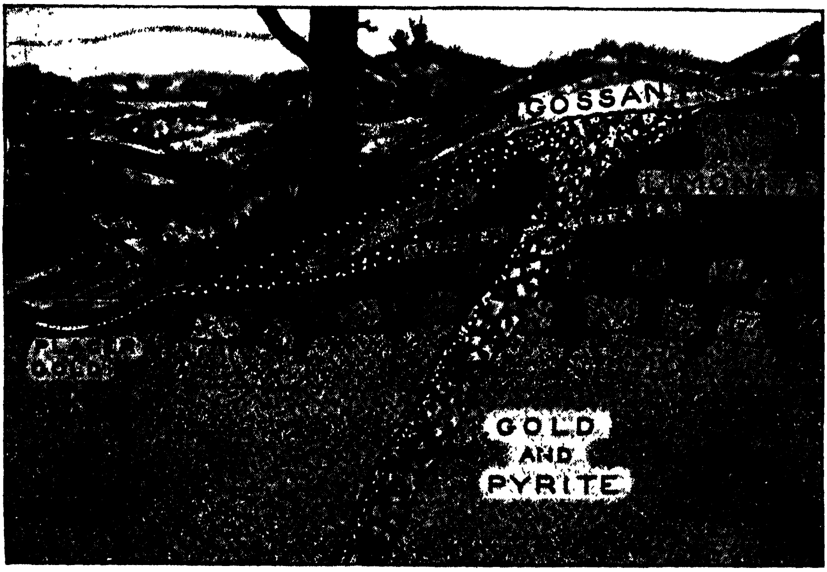

Fig. 10. The origin of gossan. An outcropping quartz vein containing pyrite and gold. The pyrite above the water table is altered to limonite. The heavy gold works down the hillside to the stream bed at the bottom. *John Jesse Hayes.*

Limonite (hydrous iron oxide) is the commonest oxidized mineral in most gossans, because of the abundance of pyrite in original ore bodies. For this reason the commonest gossans are yellow or brown in color and consist of an earthy intermixture of limonite and quartz. Valuable ore deposits, especially those of copper, may underlie limonite gossans that are valueless because the metals (other than iron) have been leached away. Many ore bodies have been discovered by sinking a shaft on a gossan and exploring the unaltered ore beneath In other cases, however, the deposit is worthless because the underlying primary minerals are quartz and pyrite only.

Mineral deposits formed by weathering processes. In some cases the gossans overlying unoxidized ore deposits contain metallic minerals in sufficient quantities to be exploited. Primary minerals containing lead, zinc, copper, and silver oxidize so readily that some gossans contain oxygen-bearing compounds of these metals. Such gossans ordinarily are limited in volume; hence most mines exploiting an oxidized ore body soon run out of such material. However, where the zone of weathering is thick, as in arid regions, and where leaching by percolating ground water has not removed the oxidized compounds, mines may operate successfully in the gossan zone for many years. Copper minerals in the zone of oxidation are especially susceptible to leaching, but the copper in some cases is reprecipitated at lower depths. This process, known as the secondary enrichment of an ore deposit, is described in the next chapter since ground water is also involved.

Weathering has contributed to the formation of other valuable mineral deposits, especially ores of aluminum, iron, and manganese. These are the leading metallic elements in the earth's crust, which comprises eight per cent aluminum, five per cent iron, and nine-tenths of one per cent manganese. Ore deposits of these elements are the result of processes which increase the original proportions. Since such concentration is confined to the zone of weathering, deposits formed in this way occur at or close to the surface of the earth at the time of their formation, although later they may be buried by great thicknesses of rocks. Several other minerals that owe their occurrence in commercial quantities to weathering are described below.

Clay. Decomposition of feldspar into clay has already been mentioned. A few rocks consist almost entirely of feldspar. When such rocks decompose, high-grade *residual* clay deposits generally result. The best chinaware clays have this origin. However, the most abundant rock in the earth's crust is granite, principally a mixture of feldspar and quartz. Weathering changes this rock to clay and quartz. Because of the presence of quartz, such clay is not of commercial value, but it may subsequently be naturally sorted by water, the clay deposited in one place, and the quartz sand in another. Thus, a sedimentary, or *transported,* clay deposit is formed.

Aluminum ore. Aluminum ore is evolved by a combination of decomposition and leaching under special climatic conditions, which are assumed to be high humidity and subtropical temperatures because most of the commercial aluminum deposits of the world are confined to such areas. The primary mineral from which aluminum ore, too, is developed is feldspar. Under humid, subtropical climates, *bauxite,* an earthy mixture of hydrated alumina minerals, is formed rather than clay (Figs. 11 and 12). Clay contains silica in addition. Therefore, when bauxite is formed during the decomposition of the feldspar, silica is leached from the rock.

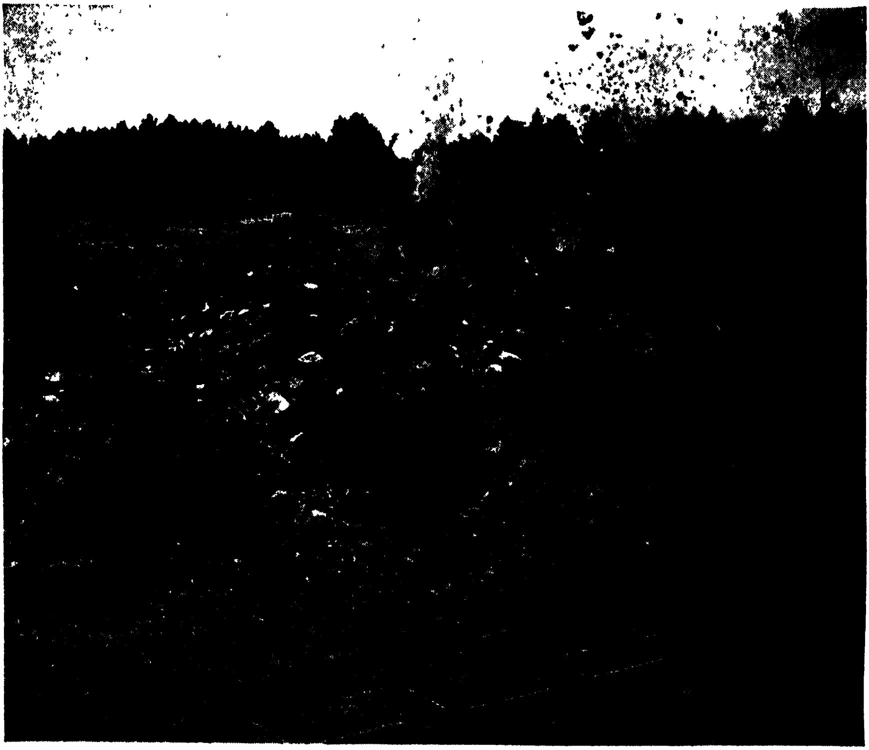

Fig. 11. Open pit bauxite mine. The bauxite ore is being blasted preparatory to loading into mine cars. ***Courtesy Aluminum Company of America.***

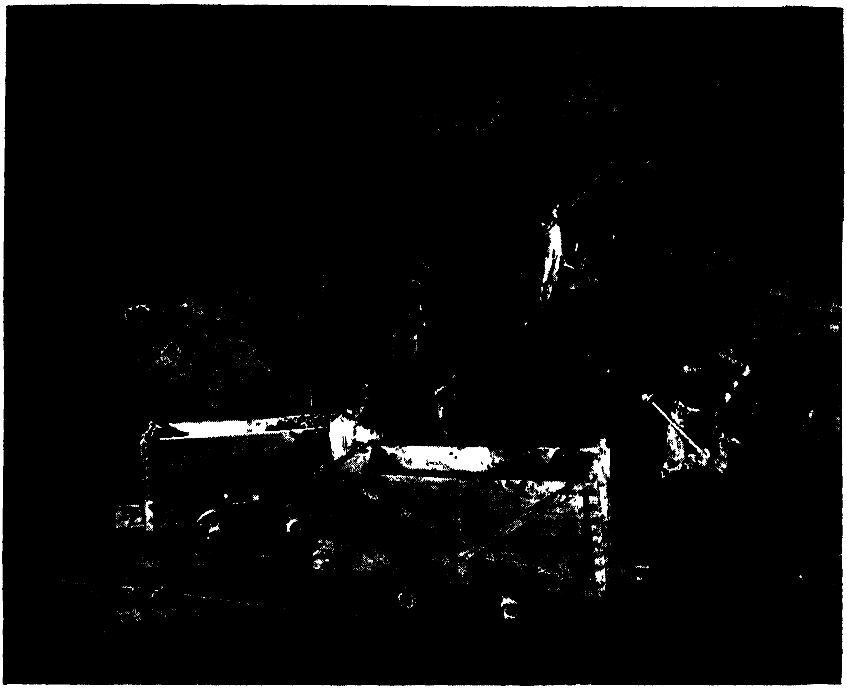

Fig. 12. Underground mining of bauxite. *Courtesy Aluminum Co. of America.*

Oxidized iron ore. Almost all of the great iron deposits of the world have been developed by decomposition accompanied by either the leaching of valueless rock or by secondary concentration. The iron which is scattered through the earth's crust with an average concentration of five per cent occurs in different forms, such as the sulphide called pyrite, the oxide called magnetite, and various silicates. The first step in the formation of an iron deposit is the chemical decomposition and oxidation of the primary iron-bearing minerals to hematite, another iron oxide. Hematite is then concentrated by leaching of the associated minerals by ground waters, or by further solution of the iron itself and its redeposition as either hematite, limonite (hydrous iron oxide), or siderite (iron carbonate). For a commercially valuable ore deposit (Fig. 13), the iron content of the rocks must be increased from the initial five per cent (higher in some rocks, especially lavas) to thirty-five or forty per cent.

Oxidized manganese ore. Most manganese ores are composed of black or brown earthy minerals. Manganese is present

Fig. 13. Open pit iron mine. Plymouth Pit, Wakefield, Michigan, August, 1939.
Courtesy Pickands, Mather, and Company.

in the rocks of the earth's crust as a relatively minor constituent of several silicate minerals. Decomposition of these minerals frees the manganese, which combines with oxygen to form one of several manganese oxides. Subsequently these minerals may be either further concentrated by leaching of associated valueless material, or transported and redeposited into concentrated sedimentary beds.

Oxidized uranium ores. Pitchblende and other primary uranium ores decompose to produce oxidized minerals which are notable for their bright orange and yellow hues. Such oxidized ores are exploited for their uranium, radium, and other radioactive element contents. The Katanga, Belgian Congo district, is the world's leading source of radioactive material.

Other mineral deposits. Barite, a barium compound used for pigments and other purposes, is a good example of concentration by leaching. This mineral usually occurs in thin veins and scattered crystals in thick limestone formations. The percentage of barite in such deposits is ordinarily too small to permit profitable mining. However, because limestone is relatively soluble, it is slowly dissolved by rain and removed by running water. Barite, on the other hand, heavy and relatively insoluble in surface waters, becomes concentrated in the residual mantle.

Many other minerals are loosened and made available for transportation by leaching. For example, gold is separated from its companion minerals and is later transported to a new environment where it is often accumulated in sufficient concentration to warrant exploitation. All minerals of placer deposits are released from their original environment by weathering.

WIND

Wind is defined as atmosphere in motion approximately parallel with the earth's surface, and the work it does is, therefore, one of the geological activities of the atmosphere. The wind is one of several agents that transport material loosened by weathering. It is also a destructive force and an agent of deposition.

Origin of winds. Winds are of two general types, planetary or prevailing winds blowing over great areas of the earth, and local winds. Planetary winds blow prevailingly in one direction except when interrupted by local winds of greater velocity. Prevailing winds are due to the varying degrees of heating of the different latitudinal zones on the earth's surface. In the equatorial zone the air is continually being warmed. As it is heated it expands and rises, and cooler air moves into the equatorial zone along the surface from the north and from the south. The direction and movement of the air in this circulation is modified by the rotation of the earth. In the northern hemisphere the winds are deflected to the right and in the southern hemisphere to the left.

Prevailing winds are important geological agents in desert, plateau, and plains regions where there are few natural obstacles to retard their velocity. Some areas, such as the Great Plains of west-central United States, are so consistently "fanned" by prevailing westerly and southwesterly winds that windmills can be operated for days at a time without interruption. The picturesque windmills of the Netherlands are turned by the same westerlies.

Local winds are due either to differential heating of the earth's surface on a lesser scale than world-wide, or to *cyclonic* storms. The rays of the sun warm the surface of the land more than they do the waters of lake or ocean, so that during the sunlight hours there is a steady movement of air off the water onto the land to take the place of the heated and expanded air in the latter area. At night, however, the temperature conditions are generally reversed and the air moves in the opposite direction. This same process also acts through a seasonal cycle under favorable conditions. For example, southern Siberia becomes hotter in summer and cooler in winter than the Indian Ocean. Therefore, the local winds, known as the *monsoon winds,* blow across India from the southwest during the summer and in the opposite direction during the winter. Mountainous areas heat faster during the day and cool down more at night than adjacent lowlands, so that local winds blow up the slope during the day and down the mountain flanks at night. Sometimes the winds in the upper atmosphere, which are the prevailing planetary winds, blow in the opposite direction to those near the ground.

Cyclonic winds are produced by areas of low atmospheric pressure which move at the rate of about 700 miles a day from west to east in the northern hemisphere. Storm winds are caused by air flowing into the low pressure zones. The velocity of these winds depends upon the differences in pressure and distances between centers of low and high pressure. The steeper the "gradient," the faster is the wind. Local winds also are capable of both destructive and constructive geologic work.

METHODS OF WIND WORK

The wind first picks up a load of rock fragments and other debris and then transports and deposits it. Deposition is not necessarily final, for a particle fine enough to be carried by the wind may be picked up, carried, and dropped many times before reaching a resting place secure from further wind activity.

Source of material. Most of the material picked up by the wind is already lying loose on the earth's surface. Some, however, may be obtained through *abrasion* or wear of exposed rock faces. Volcanic eruptions also contribute great quantities of finely divided rock particles to the moving air.

The most abundant loose material at the earth's surface is the rock mantle. Other types are sediment dropped by preceding winds, sediment deposited by streams during high water or by waves and currents on lake and ocean beaches, and volcanic fragments. Wind does not move wet soil and sediment, or soil and sediment protected by a cover of vegetation; hence the most vigorous wind erosion does not occur in humid regions. Where vegetation is scanty or absent, as in stream beds at time of low water, on beaches, and in other places because of destruction by fire, overgrazing, or cultivation, steadily blowing wind dries the loose material at the surface and makes it available for transportation.

Abrasion is wear by rubbing. Winds abrade by blowing sand and other rock particles against an exposed surface, such as a rock cliff. The particles themselves are reduced in size by frequent collision with each other and with the bed rock. Moving air without "tools" is powerless as an abrading agent, but rock can be worn appreciably by sand blown against it. A familiar example of this action is the sand blast used in cleaning the walls of buildings and other surfaces. Compressed air blows sand from a nozzle against the stone. The sand grains cut into the rock and remove the grimy surface layer so that underlying clean rock is exposed. Similar sand blasting takes place in nature, and exposed rock surfaces in sandy, windy regions are thus worn away. The material removed becomes part of the load carried by the wind.

Volcanoes eject fine material into the air, both by violent explosions which shatter solid rock, and by the eruption of molten rock into the air as spray, which solidifies into fine particles of rock glass. Both of these volcanic products are called *volcanic ash.* x

Transportation. The wind carries its load (1) by rolling the particles along the surface of the ground, (2) by intermittently lifting and dropping the grains so that they move in a series of jumps, or (3) in suspension in the air. The transporting power is dependent upon wind velocity, hence the manner in which a particle is carried depends both upon its weight and upon the strength of the wind. A violent wind may carry in suspension a grain which a gentle breeze can only roll along the surface. Many particles are too heavy even to be rolled except during times of high wind velocity.

Essential for large scale transportation by rolling are winds which are fairly constant in direction, a ground surface that is not too rough, and an abundant supply of material of the right size and weight. As they are moved along, the grains are rounded and worn, and eventually may become small enough to be lifted into the air without any increase of wind velocity.

Variations in wind velocity and direction, due in part to irregularities of the ground surface which produce local upward currents of air, cause the rock particles to be transported in a series of jumps. Between jumps the grains may be rolled along the surface or they may remain where they fall until there is another gust of wind with sufficient power to pick them up. The particles transported in this manner also are worn by friction, and eventually they become fine enough to remain in the air for longer periods of time.

The finest dust particles can be carried in suspension. However, all wind-borne sediment is heavier than air and will settle down onto the earth's surface when the air is not in motion. Wind not only moves horizontally, but it may also move upward locally because of deflection by hills and ridges and because of inequalities in the heating of the earth's surface by the sun. Dust which is fine enough to be carried into the upper atmosphere may be transported for long distances before the air becomes sufficiently still to permit settling. Very fine volcanic ash thrown out by the volcano Krakatoa in the East Indies in 1883 was carried in the upper air currents completely around the world. Dust from the so-called "Dust Bowl" of the southern Great Plains of the United States traveled to the eastern seaboard in 1934 and in subsequent years.

Deposition. Deposition of wind-borne material takes place because of decrease of velocity or change of direction of the wind. Particles dragged by the wind will come to rest when an obstacle such as a rock, shrub, fence, building, or hill is encountered.

Fragments in suspension in the air settle down onto the earth's surface and increase the quantity of the rock mantle. Because these wind deposits in most places are relatively thin, their quantitative importance is not always appreciated. Yet the wind, no doubt, transports and deposits much more dust each year than it does sand. Even in historic time the fall of dust has been of considerable magnitude in many regions. "At Nineveh, Babylon, and many other Eastern sites, mounds which have been practically untouched by man for many centuries consist of fine dust and sand gradually drifted by the wind round and over abandoned cities, and protected and augmented by the growth of vegetation. In those arid lands, the air is often laden with fine detritus, which drifts like snow round conspicuous objects and tends to bury them up in a dust drift."[1]

Of course, the sediment that is dropped may be picked up again by later winds. Fragments that have been rolled along and stopped by an obstacle may in time completely cover it, and then their onward march will be resumed. Most wind-transported fragments are eventually dropped or driven into bodies of water, adding to the sediment deposited in beds of streams and on the floors of lakes, seas, and oceans. Almost equally effective sanctuary is offered by regions covered with abundant vegetation, especially forested areas.

RESULTS OF WIND WORK

The results of wind activity include denudation or lowering of land areas, erosional features made by wind sculpture, and several types of sedimentary deposits.

Denudation. Denudation is the removal of material lying at the surface. The wind is one of several agents performing this work. Wind denudation is known as *deflation.* A quantitative estimate of the amount and rate of deflation is difficult to make. Geikie[2] cites an estimate that about eight feet of soil has been swept off the Nile delta during the last 2,600 years—a rate of nearly four inches per century. He also describes old fortifications in northern China the foundations of which have been laid bare by wind erosion. When one observes the amount of dust that is borne through the air by a high wind lasting but a few hours and considers what this volume would be over a geologic period millions of years in length, he begins to appreciate the importance of wind denudation. Furthermore, in the earlier geologic periods there was little or no vegetation on the land, and the grasses, the most important soil retainers of all, did not become widespread until late in geological time. Hence, wind erosion must have been far more important in the past than it is today.

Wind sculpture. Abrasion by the wind produces a number of curious effects, especially in deserts and other areas of low rainfall where the lack of vegetation makes for maximum exposures of rock surfaces, minimum impediment to wind velocity, and an abundant supply of "tools" with which the wind abrades. Rock surfaces become polished, pitted, and grooved by the grinding and polishing effect of wind-driven sand, and individual pebbles may have triangular faces cut upon them.

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[1] Geikie, Sir Archibald, *Text-book of Geolog* 4th edition, Vol. I, pp. 438-439. London: Macmillan and Company, 1903.

[2] Geikie, Sir Archibald, *op. cit.,* Vol. I, p. 435.

Winds scoop out shallow depressions ("blowouts") on the earth's surface, where the rock mantle does not have a protective cover of vegetation. Many small lakes, both intermittent and permanent, lie in such wind-scooped basins.

DEPOSITS

Wind-blown deposits are part of the transported rock mantle. These deposits may overlie older mantles, either residual or transported, or they may cover bed rock surfaces. Transported mantle, formed by wind or running water, differs from residual mantle in that the material composing it is either stratified, due to the sorting effect of the transporting medium, or is homogeneous in size.

Dunes. Sand dunes are the best known of the wind deposits. They originate because of the accumulation of sand which has drifted along the surface until piled up by an obstruction. The sand may have come originally from the banks of a river, the bed of a dry water course, a lake or ocean beach, from a desert basin, or it may have been freed by the disintegration of sandstone. Sand dunes are most abundant (1) in desert regions where the dryness and the lack of vegetation make an abundance of loose material available, (2) along coasts where a combination of onshore winds and a supply of beach sand is favorable to their growth, and (3) in the vicinity of rivers, especially on the leeward side where sand from the river bed and banks is picked up by winds blowing across the river. River dunes are most common where a stream passes through a semi-arid belt and its water sinks out of sight during dry seasons so that sand deposited by floods is exposed to the wind. Dunes may occur also in upland areas of average rainfall where sandy soil in fields exposed to a broad sweep of wind has been laid bare by cultivation. Such dunes are most abundant in areas of seasonal rains where the surface soil becomes exceedingly dry during the rainless periods.

The obstruction which impedes the drifting of sand may be a tree, a bush, a small topographic irregularity, a boulder, a fence, or even a house. Once a small sand hill or dune has been formed, the dune itself acts as an obstacle and growth continues, so that eventually the dune may be many times higher than the original obstruction. If the wind causes the dune to migrate, the obstruction may be left behind, perhaps to serve as a nucleus for the building of a new dune at that point.

Some dunes appear to be stationary, others are migratory. They move, of course, in the direction of the prevalent wind. Forward motion is not accomplished by actual pushing of the dune, but by removal of grains from the windward side and deposition on the leeward. Sand grains are picked up by the wind at the base of a dune, blown up the slope in a "stream" several inches high and over the top where gravity causes them to roll down the relatively steep slope on the other side toward the base of the dune. Repetition of this process by every grain of sand in a dune will move the dune forward its own width.

Sand dunes vary greatly in shape and size. One very characteristic type has a quarter-moon outline. Of the many others, some are circular or elliptical in plan, a few are very elongate or ridgelike, and quite a number are so irregular in form that they cannot be classified (Fig. 14). The linear dunes are created by winds predominantly from one direction; circular and irregular forms result from variable

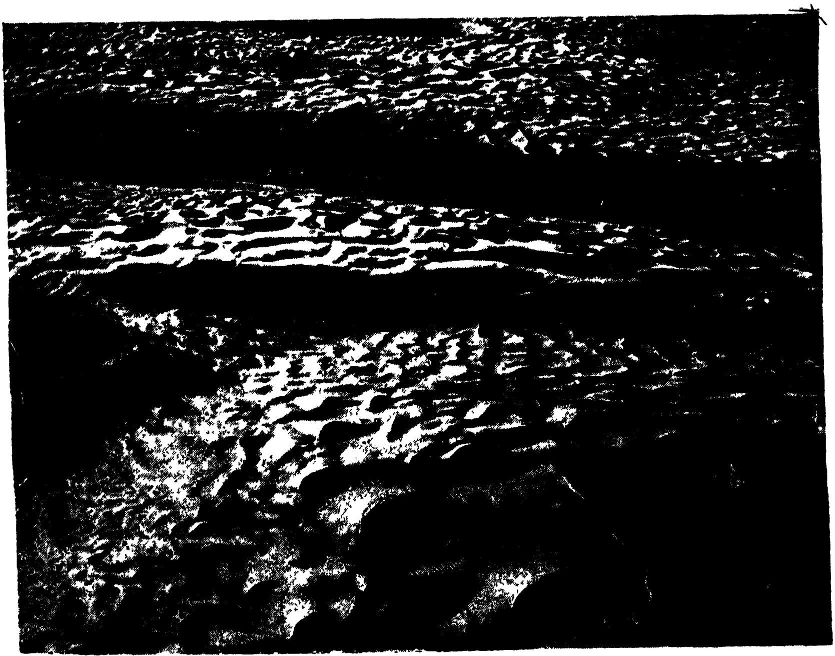

Fig. 14. Sand dunes of irregular shape in Imperial County, California, west of Yuma, Arizona. ***By permission Spence Air Photos.***

winds. Many dunes, regardless of plan, have the same general shape in cross-section. The slope in the direction from which the wind comes is gentle, whereas the slope on the leeward side is steep. Windward slopes are made by the force of the wind itself. The steepness of the leeward slope is, of course, dependent upon the angle of repose (steepest slope at which loose material will stand) of the sand. If the sand is rounded, the angle of repose will be less than if the grains are somewhat angular and consequently have a tendency to interlock.

The height of sand dunes varies greatly. The average the world over is probably considerably less than fifty feet. The sand dunes on the southeastern shore of Lake Michigan reach heights of 100 and 200 feet, as do the dunes in the deserts of Australia. Probably the largest sand dunes are in Great Sand Dunes National Monument, Colorado, where some exceed 500 feet in height and may reach 1,000 feet (Fig. 15). The length of an individual dune also varies greatly. Most of them do not exceed a quarter of a mile in length, but in deserts where there are great areas of parallel dune ridges, each one may be many miles long.

Quartz, because of its abundance in the rocks of the earth's crust and its resistance to chemical decay, is the dominant mineral in most dune sands. However, a special type of sand dune is found on coral islands, such as the Bermudas, where on-shore winds have caused the accumulation of thick deposits of small rounded grains of limestone produced by wave erosion of coral reefs. Rain water percolating through the limestone sand dissolves calcium carbonate and reprecipitates it as cement between the grains. In a relatively short time, these calcareous dunes become limestone rock.

Another unusual dune sand is found in the White Sands National Monument in southern New Mexico, where glistening white gypsum sand in dunes up to 60 feet high covers an area of more than 500 square miles. Here the animal life has adapted itself to its environment by a change of color. Lizards and mice are white, and even some of the insects are extremely light in color.

The scooping of shallow lake basins by the wind has been described. In such basins excavated between dunes, small lakes are occasionally present. More often, however, the high permeability of the sand does not permit the existence of lakes in the interdune depressions, except during wet seasons when the water table is abnormally high.

Most dunes are furrowed by *ripples* which lie parallel to each other and at right angles to the direction of wind movement. Ripples are miniature dunes. They move slowly up the windward slope of a dune until the crest is reached. Some have suggested that ripples, occurring on a sandy surface, can initiate dunes without the assistance of vegetation or other obstacle.

Because wind is a very effective sorting agent, all of the sand grains in a dune are nearly equal in size. The surface of the quartz grains commonly are roughened or *frosted* because of wear during transportation.

Migrating dunes often cause considerable damage. If they advance onto tillable land, it may become valueless for agricultural purposes. Trees and even forests have been entombed by traveling dunes. The tops of trees project above the dunes on the southeastern shore of Lake Michigan. Advancing sand dunes may seriously interfere with streams, since they dam valleys and force streams to find new channels. Even towns have been overwhelmed by advancing dunes. Lyell states "The burying of several towns and villages in England, France, and Jutland, by blown sand is on record; thus, for example, near St. Pol de Leon, in Brittany, the whole village was completely buried beneath drift sand, so that nothing was seen but the church spire."[3] After burying a forest or a village, dunes may march on, leaving behind a devastated countryside of dead trees and collapsed buildings. Dunes move so slowly that it takes several decades for advancing sand to bury an object and expose it again by migrating onward.

Although most dune-covered areas are waste lands from a standpoint of soil productivity, they are not without scenic interest. The unusual topography, combined with the bleakness and barrenness of the dunes, gives such regions a certain amount of charm. For this reason, the United States has created the Great Sand Dunes National Monument in the San Luis Valley of southern Colorado. Within this national monument, which covers approximately 46,000 acres, are the highest sand dunes in the United States, if not in the world. They have been formed by the prevailing winds from the west driving sand across the San Luis Valley, the bed of an ancient lake. The sands are entrapped in a great embayment in the Sangre de Cristo Mountains, which form a scenic background for the Great Sand Dunes (Fig. 15). The dunes are visible for many miles to the traveller who approaches from the west, and they loom larger and larger as he gets closer. The fact that they are hills of loose sand becomes increasingly difficult to believe. But when the traveller reaches them and starts the laborious climb up the "world's largest sand piles," he is quite convinced of their real nature, for walking in the loose sand is most arduous. The highest dunes are near the center of the area. Their summits lie more than five hundred feet above the floor of San Luis Valley. Between many of the dune summits are depressions, or "blowouts" several hundred feet deep. The dunes are restless; the sands move continuously up the flanks of the dunes even in a moderate wind, and a strong breeze produces streamers of sand flying to the leeward from the summits. The windward flanks of the dunes are characteristically ripple-marked.

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[3] Lyell, Charles, *Principles of Geology,* London: John Murray, Albemarle Street. p. 699, 1847.

Dunes are also abundant on Cape Cod, Massachusetts, contributing much to the fascination of this district. Another popular dune area lies on the southeastern shore of Lake Michigan.

Even from an economic standpoint dunes are not entirely without value. Because of their porosity, dune sands make ideal reservoirs for rain water, and supplies are obtained from them at several places in

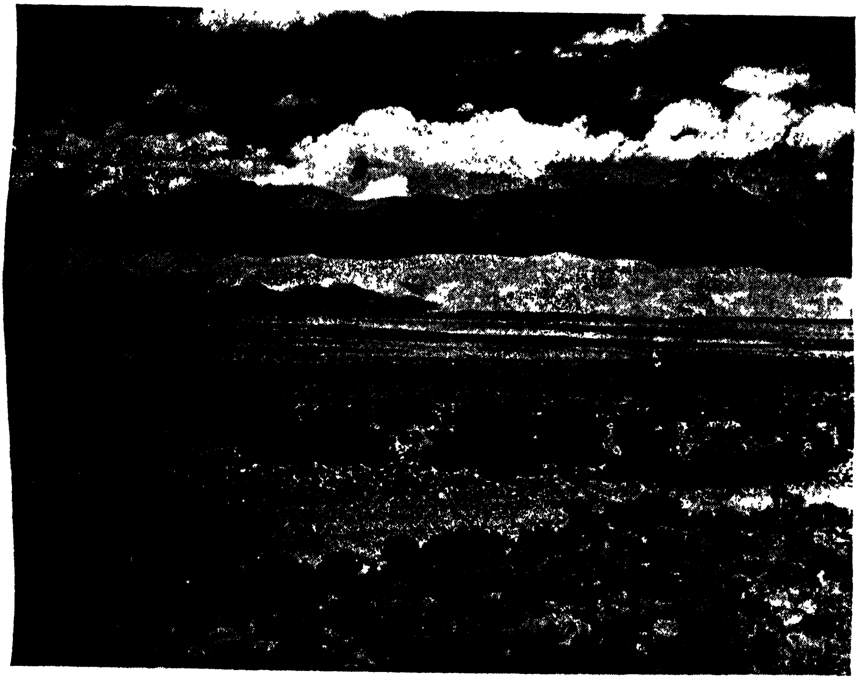

Fig. 15. Great Sand Dunes National Monument, Colorado, with Sangre de Cristo Mountains in background. ***By M. V. Denny.***

the Mississippi Valley. In some instances, the dunes overlie rock formations containing beds of salt and gypsum, so that, were it not for the supply in the loose sands, usable ground water would not be available. Furthermore, dune sands store rain water that would immediately run off otherwise, and allow it to seep gradually into the streams and give them a more consistent flow. Some dunes are exploited for the fine sand which they contain.

Loess. One type of wind blown dust known as *loess*[4] is found in thick deposits in a number of regions. It characteristically has a yellowish brown color. A microscopic examination shows that it is mainly a mixture of fine quartz, grains of feldspar, and clay minerals. The particles are angular, but effective sorting by the wind has made them remarkably uniform in size. Loess may contain freshwater snail shells, which are attracted by the high calcium content.

Perhaps the most remarkable characteristic of loess is its ability to stand in almost vertical banks where cut into by streams, valleys, roadways, or other excavations. The angularity of the particles develops considerable coherence in the deposits. Exposed faces in loess in many places show a multitude of hollow vertical tubes which extend several feet below the surface. They are root holes left after the plants have decayed, and they tend to give the loess a vertical parting. Unlike most types of sediment, loess deposits lack visible evidence of stratification.

Loess was first described from the Rhine valley in Europe, but subsequently it has been found in southeastern Europe, the Mississippi valley region in North America, and in China. The deposits in the Mississippi and Missouri River valleys, although widespread, are best developed in Iowa, Nebraska, and northern Kansas (Fig. 16). Here the average thickness of the loess is about twenty feet, but in places it is much thicker. The total volume, however, is insignificant compared with that of the Chinese loess which covers more than a half-million square miles and in places attains a thickness exceeding one thousand feet. The sweeping of this yellow dust into streams has given the Yellow River its name; and also the Yellow Sea into which the river flows. Loess deposits are exceptionally fertile, so loess-covered regions are intensively cultivated where the climate permits.

The impalpable character of the material combined with its wide-

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[4] This word is variously pronounced as though it were spelled *lois, less, luss, lerss,* and *löss.* The last is the recommended pronunciation. but many people find the German umlauted "o" difficult.

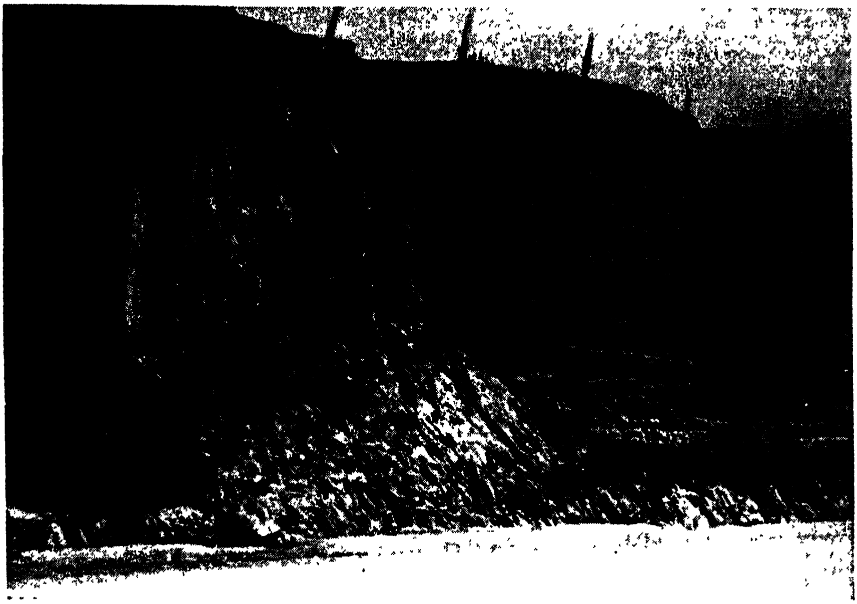

Fig. 16. Loess in highway cut east of Highland (Doniphan County), Kansas. *By W. H. Schoewe.*

spread geographic distribution has led most geologists to conclude that loess is a wind deposit. On the North American continent the deposits are thickest and most abundant around the borders of the great, geologically recent ice sheets. This fact, taken with the heterogeneity of mineral composition, has led to the theory that some of this loess, at least, was originally glacial sediment which was ground to fine powder by ice and subsequently blown over neighboring areas. There is no doubt that much of the material was transported for some distance by the rivers draining the glaciated areas before being picked up by the wind. In other parts of the world, notably in China, the loess has had a different origin. The source of the Chinese loess is known to be disintegrating rock surfaces in the Gobi of central Mongolia.

Volcanic ash. Wind-blown deposits of volcanic ash or dust occur near the Pacific border, in the Rocky Mountain states, and on the Great Plains, especially in Kansas and Nebraska. The Great Plains ash was probably ejected by the Capulin group of volcanoes in northeastern New Mexico during the same relatively recent epoch when various parts of the world were glaciated. The prevailing southwesterly winds carried this ash over parts of Colorado, Oklahoma, Kansas, Nebraska, and even into western Iowa. When it first settled out of the air it was thinly, but rather evenly, distributed over a very broad area. Subsequently the wind drifted the ash, and much of it was blown into streams and borne seaward. A few of the drifts, however, came to rest in depressions or lakes where they were protected from further erosion by wind and running water, and so have been preserved to the present day. Some of these deposits are exploited, mainly for use in household cleansers and silver polishes, because of the angularity and hardness of the minute grains. A few examples of scattering of volcanic ash by wind during historic times will be described in Chapter 10, on vulcanism.

Placer deposits. The concentration of relatively heavy minerals by a transporting agent produces placer deposits. Most deposits of this type occur in the beds of streams where running water was the transporting and sorting agent. However, wind also sorts materials according to their weights, and, if a wind-blown sand contains minerals of varying specific gravity, the heavier minerals will not be carried as far as the lighter and will become concentrated during deposition. Diamond deposits of this type are exploited in an extremely arid region in southwest Africa.

WIND AND MAN

Man has used wind as a source of power on both land and sea throughout historic time, but he has also suffered, and still suffers, from damage by activity of the wind.

Hurricanes and tornadoes. The strongest winds are those accompanying two special types of storms: hurricanes and tornadoes. As compared with cyclonic storms, hurricanes have a small diameter but are of great violence. They originate over tropical oceans. Hurricanes may cause considerable damage to shipping and, when they move over the land, general devastation results. The Gulf and South Atlantic coasts of the United States have been visited by a number of storms of this type. The hurricane that devastated Galveston in 1900 blew with a velocity of 80 to 100 miles per hour and carried away the wind-recording instruments at the Government weather bureau. Subsequently, the wind increased to an estimated speed of 120 miles an hour. Wind of such velocity tends to level everything before it. Sand, pebbles, boulders, and even large slabs of loose rock are swept through the air. Trees are uprooted and houses and buildings blown down. Some of the Florida cities have been almost destroyed by hurricane winds, and huge waves that accompany hurricanes attack the shore with spectacular vigor.

A hurricane as devastating as it was unexpected visited New England in the early fall of 1938. This storm ranks first among those occurring in the United States in terms of property damage, which amounted to several hundred million dollars. Here are excerpts from an article describing the New England hurricane:

> The wind's destruction commenced about 2:30 p.m. along the south shore of Long Island, and ceased above the Canadian border after midnight. The disaster was three-fold. Over sea beaches storm waves of the hurricane, few in number, but towering as high as 40 feet, swept everything away. Terrific winds carried destruction inland. Torrential rains swelled streams, already flooding from earlier downpours.
>
> Seven states and the Province of Quebec counted close to 700 fatalities. A seaboard as wealthy as any in the world, and its hinterland . . . felt the shock. There had been no warning worth the mentioning; telephones and coast-guards were scarcely called to service. A sophisticated population died by hundreds with little or no knowledge of what raw shape of death this was which struck from the sky and the tide. . . .
>
> Not until almost midafternoon of September 21 did the rapid fall of barometers in New York City itself suggest to Weather Bureau officials cloistered in office buildings that the dreadful invader from the south had refused to follow precedent by recurving northeast to open sea. By three p.m. the warning went out from New York City that a hurricane center would pass over Long Island and Connecticut late this afternoon or tonight, attended by shifting gales. Even this tardy warning was not adequately spread, and already the inner spirals of the wind were screaming against Long Island.
>
> Days before, while the fledgling hurricane still was swooping northwestward from its nest in the doldrums, experienced Florida had battened down. But there were no preparation made Wednesday afternoon from Cape May to Maine. Dwellers in summer cottages and fishing settlements remained uninformed of peril until the unchained wind and sea informed them. Meteorology long has taught what the effects are when a hurricane crosses a coast line. For far too many people that afternoon the knowledge came too vividly and too late. . . .
>
> The south shore of Long Island and the exposed Connecticut and Rhode Island shores east of Montauk Point faced the full force of the seas. Along these coasts beach after beach was scoured. At West Hampton of a 30-room mansion no single vestige remained. Seventeen refugees huddled chest deep in sea water on the second floor of one when the walls at last gave way. Survivors lost not only their

> houses; many lost houses and lots; for the beach was deeply channeled. In Suffolk County the reduction in assessed valuation of real estate is estimated at $50,000,000. Elaborate lawns a mile from the sea at Quogue were under breakers two feet high; a cottage washed across with ten people on its roof. . . .
>
> Long Island Sound was beaten to one unbroken sheet of foam. Both shores were invaded by wind-driven tides. Along the mainland coasts from Stonington to Buzzards Bay, where Long Island no longer serves as a breakwater, the storm waves were murderous. Narragansett Bay suddenly flooded downtown Providence. People who watched the surf were snatched into the sea, even from behind the steering wheels of their cars.
>
> From the seacoast to the border, from western Maine to eastern New York, there was wicked damage to trees. As example: of a grove of 40 noble white pines around a cottage on Lake Winnepesaukee, 39 are down, several across the cottage. Of 3,000 sugar maples in one planting in central Vermont, 100 were counted standing.[5]

Tornadoes are low-pressure storms even smaller in diameter than hurricanes. Instead of being measured in terms of many miles, the path of devastation left behind by a tornado may be but a few yards wide. The wind rushing in toward the center of a tornado may move at three or four hundred miles per hour. It follows a circular or spiral route into the low presssure area. Damage is done both by the excessive force of the winds that are drawn into the abnormally low pressure area at the center and by the low pressure itself. When the "core" of a tornado surrounds a building it is as though the structure had suddenly been plunged into a chamber in which a partial vacuum exists. The air pressure inside is much greater than outside and unless there are sufficient avenues for sudden escape of the inside air the structure literally explodes, and the walls fall out.

To an onlooker from a distance, a tornado appears as a large black funnel-shaped cloud with the tapering end of the funnel hanging downward (Fig. 17). As the tornado travels across the country the funnel swings back and forth, like an elephant's trunk, the tapered end sometimes brushing the ground and at other times rising high into the air. Wherever it drops and wherever it swings devastation results (see Figs. 17, 18, and 19). In passing through a city a tornado leaves in its wake a path like that made by a lawnmower when pushed through high grass. Houses on one side of a street may be completely razed, whereas those across the street remain undamaged. Lifting of

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[5] Stewart, John Q., "New England Hurricane," *Harpers Magazine,* January, 1939, pp. 198-204.

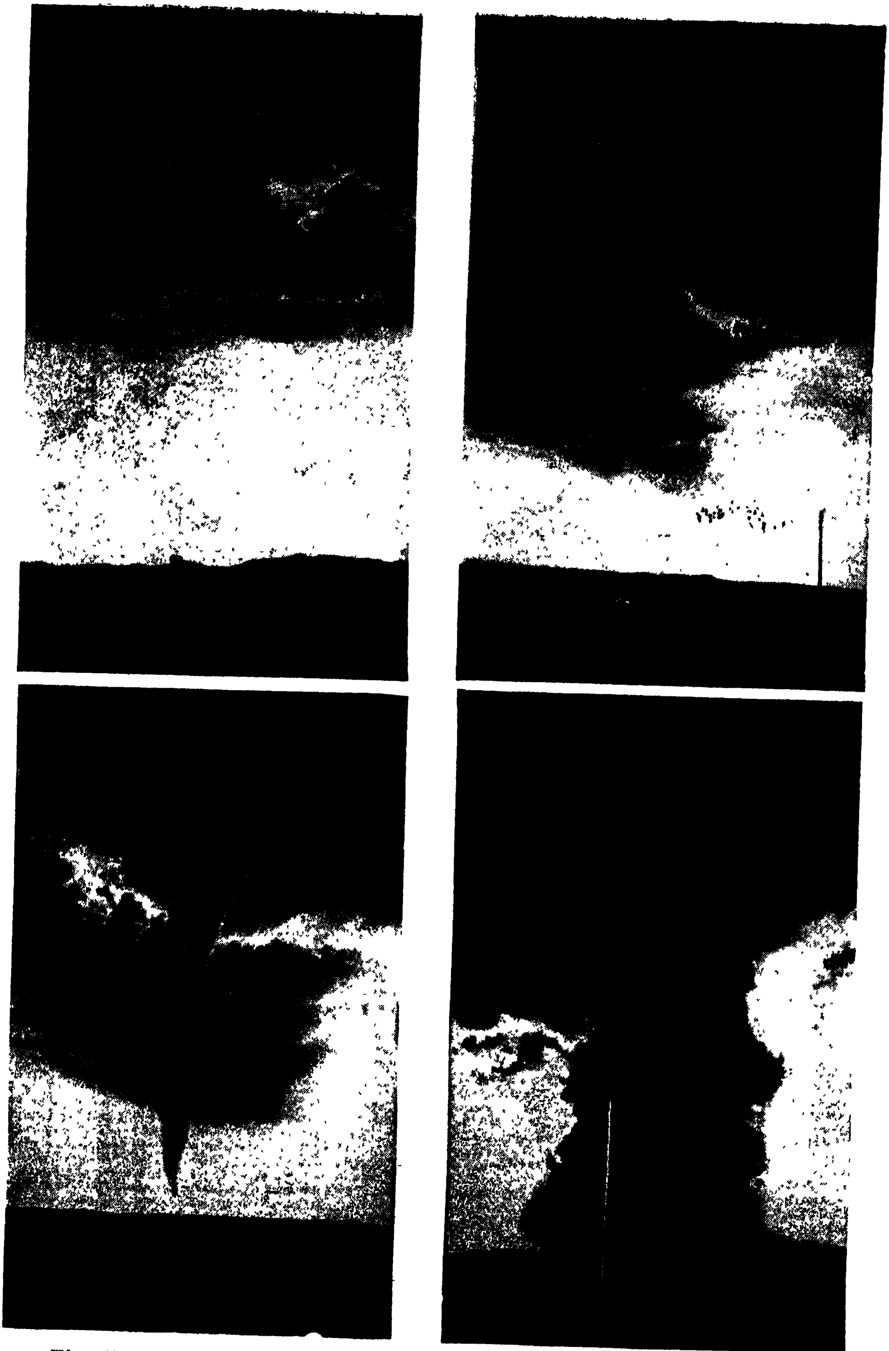

Fig. 17. A tornado strikes near Gothenburg, Nebraska. Upper left: The storm clouds before the tornado appears. Upper right: the tornado appears. Lower left: The tornado approaches. Lower right: The tornado strikes.

Keystone View Company.

Fig. 18. After the tornado strikes. Columbus, Kansas, March, 1938. The tornado came in at lower left, crossed the picture area to the lower right, turned and proceeded diagonally across picture to upper left where freight cars on siding were overturned. *By Jack Wally. Courtesy Kansas City Journal Post.*

Fig. 19. Freight train after the tornado passed. Near Medicine Lodge, Kansas, May 7, 1927. *Binning Photo.*

the "trunk" here and there explains the occurrence of entirely undamaged areas along a tornado's path. The destructive action of tornadoes has been tersely described by Milham in the following words:

> Due to tornadic action, large trees are stripped of their branches, broken off near the ground, or torn up by the roots; heavy brick and stone buildings are crushed and destroyed as if they were card houses; tin roofs are torn from buildings and are carried many miles through the air; loaded cars and even locomotives have been blown from the track; heavy iron girders have been carried over the tops of buildings; iron bridges have been moved from their foundations. Straws have been driven through boards, laths through trees, and small sticks of timber through iron plate. When the funnel cloud strikes a building, it often seems to explode. The roof is carried up and the side walls fly apart. Chests explode; corks are drawn from empty bottles; chickens are stripped of their feathers. Soot is often seen to rise in quantity from the chimneys of nearby houses and window panes often fly outward.
>
> The noise which accompanies a tornado is tremendous. It has been likened to the noise of a thousand express trains rushing through tunnels or to the sound produced by thousands of wagons loaded with iron and moving rapidly over an uneven pavement. The uproar is so great that the crash of individual buildings is seldom heard.[6]

Dust storms. The decade of 1931-1940 saw many severe dust storms in the United States. Much of the dust came from the so-called "Dust Bowl" in the southern Great Plains which includes parts of Colorado, Kansas, Oklahoma, Texas, and New Mexico. Usually, as during the 'thirties, the abundant dust becomes available because of destruction of the protective cover of vegetation by overgrazing and improper cultivation, followed by a period of prolonged drought. The wind, which persistently sweeps across this flat area, picks up the exposed dry soil, forming an immense cloud reaching high into the air and transports the dust for varying distances. To the onlooker, an approaching dust storm most often appears as a sharp, dense black cloud (Fig. 20). This "blackout curtain" reaches to the ground and when it arrives blots out the sun so that semidarkness follows. A second type of dust storm is heralded simply by a gradually increasing haziness of the air. With the storm's arrival, swirling dust penetrates every possible opening. Housewives seal the cracks around the edges of windows and doors with adhesive tape in

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[6] Milham, W. I.. *Meteorology*. New York: The Macmillan Co. 1929 pp. 336-337.

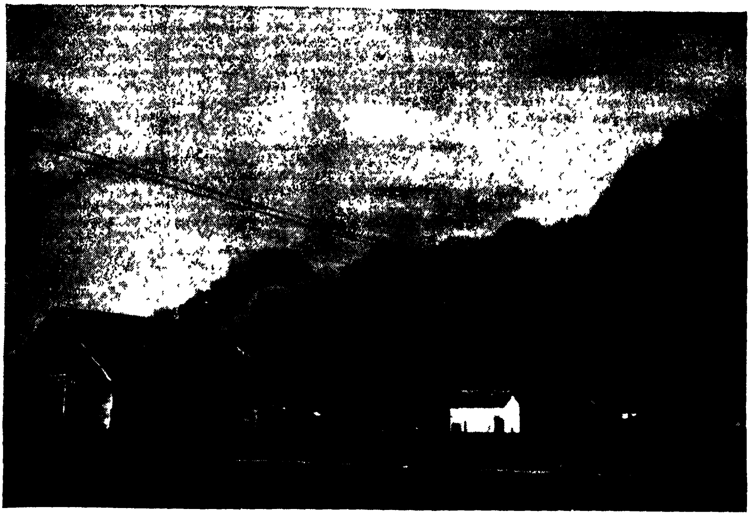

Fig. 20. A dust storm comes to town. *Conard Photo.*

order to reduce dust infiltration. Outdoors all traffic, even movements of trains during the severest storms, comes to a standstill. Automobilists find that at times the limit of their visibility is the radiator cap. Even pedestrian travel is hazardous, and children are kept at school or at home, until the storm abates. Fine dust clogs the nostrils, making dust masks advisable. With the passing on of the storm, the dust becomes thinner and travel can be resumed. The sun reappears, but, as do automobile headlights and street lights, it has a peculiar bluish color caused by the dust's filtering out of the colors toward the red end of the spectrum. A thin deposit of dust blankets the countryside like a light fall of snow. The air slowly clears, and breathing becomes easy once more.

The importance to the farmer of the loss of this soil cannot be overemphasized because, as has already been pointed out, the fertile part of any soil is the top few inches (Fig. 21). Of course the dust eventually settles and adds to the fertility of the soil in other areas, but the increment received during a single decade ordinarily is slight. Over a long period of time, however, dust deposition undoubtedly has enriched the soil of many regions, and many fertile farmlands of today probably owe the richness of their soil to dust transported by the wind.

Locally, the blowing soil may tend to accumulate in drifts, due to retardation by irregularities on the surface, including those erected by man (Figs. 22 and 23). For the time being cultivation of the drifted areas is not possible.

Conservation methods of controlling wind erosion. Soil erosion has increased at such a rapid rate in recent years that the United States Department of Agriculture created the Soil Conservation Service to investigate methods for retarding the destruction. This bureau, after studying the problem, has made several suggestions, the general adoption of which doubtless would greatly decrease wind erosion of soil. Among the recommendations are:

1. Planting row crops such as corn on the contour (an imaginary line connecting all points of equal elevation) instead of north and south or east and west as ordinarily done. Where the crop rows follow the contour, rainwater and melted snow cannot escape so easily; instead they have sufficient time to sink into the soil. This additional moisture aids in retarding removal of soil by wind, and at the same time stimulates the growth of a protective cover of vegetation.

2. Instead of a solid stand of a single crop, in certain localities alternating strips of two different crops should be planted across the path of the prevailing wind. In this way the winds are diverted upward by the strips containing the taller plants.

3. The farmer should leave the stubble in the field through the

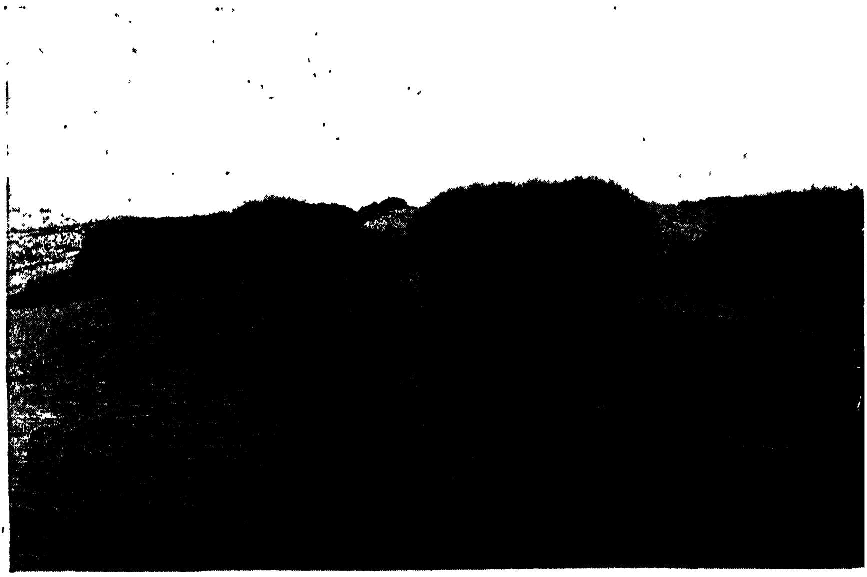

Fig. 21. Fertile soil blown away, except for hummock where vegetation has held. Holt County, Nebraska, June 6, 1936. ***Courtesy Soil Conservation Service, U. S. Department of Agriculture.***

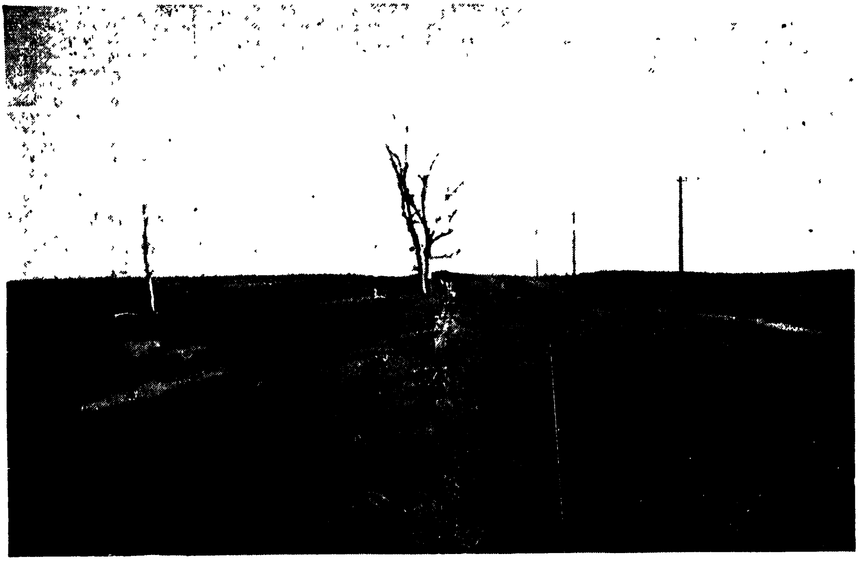

Fig. 22. Drifting soil lodging along fence and covering road. Beadle County, South Dakota, 1935. *Courtesy Soil Conservation Service, U. S. D. A.*

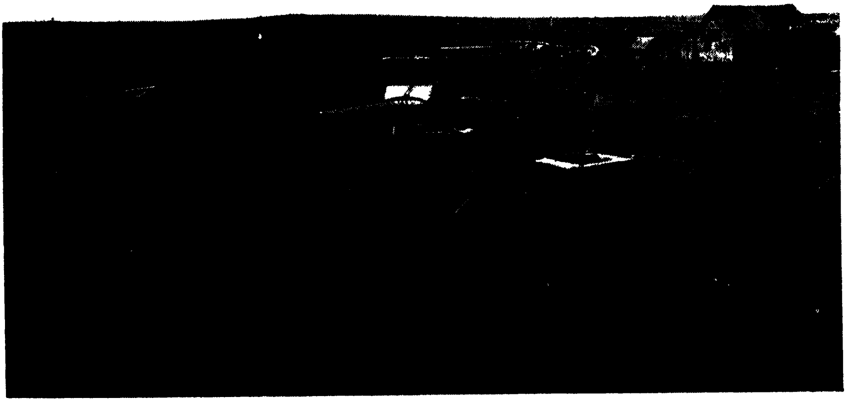

Fig. 23. Farm machinery buried beneath drifted soil. Gregory County, South Dakota, May 15, 1936. *Courtesy Soil Conservation Service, U. S. D. A.*

winter after harvesting instead of plowing it under. "The stalks help to protect the soil from blowing in winter; the roots bind the soil and keep it on the field."

4. Trees planted on the windward side of fields break the force of the wind and divert it upward, thereby reducing wind erosion and the drying out of adjacent soil.

5. Where wind erosion has already been so severe that it is difficult to get the crop started, "rough tillage" should be practiced. This method of cultivation tends to leave lumps or clods, instead of pulverized soil, on the surface, and creates a series of ridges and pockets which preferably should cross the field at right angles to the prevailing wind direction. The ridges cause some upward deflection of the wind and serve as a trap to drifting soil. The pockets provide maximum storage of rain or snow water.[7]

For some areas, major readjustments in land utilization should be made. Where soil moisture is consistently inadequate, attempts to plant staple crops such as wheat should be abandoned. In their place, sorghum, or some other cover crop, should be grown. Such crops give the surface soil much better protection against blowing because of their network of roots. Areas where it is impossible for a farmer to make a living through cultivation of the soil should never have been broken by the plow and should be regrassed where possible.

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[7] Abstracted from U. S. Department of Agriculture Soil Conservation Service, Region Nine, *Soil and Water Conservation in the Northern Great Plains,* Washington, D. C., U. S. Government Printing Office, 1937.

CHAPTER 4

Ground Water

GROUND WATER IS AN ABBREVIATED TERM for underground water. Rarely does ground water have such freedom of movement that it can erode physically; its geological work is largely chemical in character. The net effect of ground water activity is to lower the land.

Ground water is of great importance to mankind, for many regions are totally dependent upon it for water supply. Furthermore, all rivers, other than those fed by melting mountain snows, owe their permanence to the seepage of ground water into the stream-bed. Without it they would carry water only during and immediately following rains over the drainage basin.

Ground water activity has produced many places of unique scenic and recreational value, including twelve national monuments and parks in the United States.

Origin. There are several sources of ground water, but the principal one is the precipitation that falls onto the earth's surface. This water is called *meteoric* water. The volume of meteoric water that eventually reaches the ground water zone is the remainder after evaporation, surface run-off, and vegetation have taken their toll. Therefore, the amount actually received is dependent upon the humidity of the air at the surface, the speed of the fall, the slope of the surface, the porosity of rock, and the amount of vegetation. The proportion of rain water or melted water from snow and ice that becomes ground water varies widely from place to place and in a given locality from day to day. On the average, probably not more than twenty or twenty-five per cent of the meteoric water becomes ground water.

Additions to the ground water supply also occur where the *water table* (upper surface of ground water) drops below the lowest surface levels so that lakes and streams tend to drain underground. The behavior of streams in passing through regions of deep water table will be described in the next chapter.

Much of the underground water in sedimentary rock areas was deposited with the sediment and is called *connate* water. When sediment is deposited beneath water, as in a lake or an ocean, the spaces between the grains are filled with water. Thus oil wells often encounter much salt water which was trapped in the sediment at the time of deposition. As a general rule, water buried in marine sediments is more mineralized than sea water because, in the millions of years that it has been in the rocks, it has dissolved additional mineral matter.

In regions of relatively recent volcanic activity, water from deep-seated magma, known as *magmatic* water, is added to the ground water supply. Examples are to be found along the Pacific coast of North America and in Yellowstone Park.

Soil moisture. Although recoverable ground water is limited to that which lies below the water table, the zone of soil moisture is a water reservoir used by, and essential to, most plants. This zone lies immediately beneath the surface. The water stored in it is attached to the soil particles, and is removed by the roots of plants. The amount required each year to maintain plant life in most areas is several times the amount in storage in the soil zone at any one time, so the soil moisture must be periodically replenished by rainfall or irrigation. No downward seeping rain water can reach the water table until the soil moisture reservoir has been filled to capacity. For this reason none of the rain following a drought may reach and replenish the ground water reservoir.

Ground-water reservoirs. Water is present underground almost everywhere, but at widely varying depths and with considerable differences in abundance and quality. The volume of water in an underground reservoir depends upon the *porosity* of the rock. The availability of this water for use depends upon the *permeability* of the rock; that is, the ability of water to move through the open spaces. Rocks which are both porous and permeable are called *containers,* such as sandstones and rocks which are porous but relatively impermeable are *retainers.* Examples of retainers are clay and shale, which have a relatively high porosity because of the presence of a multitude of open spaces between mineral grains. These pores may be filled with water, but the openings are so minute that the water cannot move. This "fixed" ground water is in what might be called dead storage. It cannot be exploited. Still a third type of rock, such as granite or quartzite, has practically no porosity whatsoever so is neither a container nor a retainer.

Sometimes a container is known also as an *aquifer* although the latter term is customarily restricted to ground-water reservoirs containing usable water supplies.

Granular rocks, such as sandstones, are outstanding examples of ground-water reservoirs. Sand grains because of their shape cannot be packed so closely together that open spaces or *voids* are eliminated. As much as forty per cent of a sandstone may be composed of voids. A stratum of sandstone twenty feet thick and full of water would therefore contain the equivalent of eight feet of water. Since voids are inter-connecting, movement of water in any direction is possible, provided, of course, that the voids are *super-capillary* (large enough that water can flow through them).

The porosity of a sandstone depends upon three things: the degree of homogeneity in the size of the grains, the angularity of the grains, and the degree of cementation between the grains. A sandstone composed of mineral grains of approximately the same size will have greater porosity than one in which their size varies greatly, for in the latter case the pores between the larger grains may be filled with finer material. The more angular the grains, of course, the more closely they can be packed. A sandstone in which the grains have been completely cemented together has no porosity. Fortunately for many regions dependent upon underground water, this situation rarely exists. Ordinarily only a part of the pore space is filled with cement. Entirely uncemented granular material, such as sandy soil or sandy flood plain alluvium, has maximum porosity and can store a large quantity of water.

Water also occurs in solution cavities, such as limestone caverns, through which the water flows as underground rivers. More commonly the cavities are small and the water moves through them very much as it does through the pores of a sandstone. A limestone known as the "Arbuckle" lies deeply buried under many thousands of square miles in the mid-continental part of the United States west of the Mississippi River. Its uppermost thirty or forty feet is very porous because of ground-water solution many millions of years ago when the limestone lay near the surface. This porous zone is full of water except locally where oil has taken its place. The reservoir conditions for the underground storage of oil and gas are the same as those for water.

Lava flows are characteristically porous in their upper portions because of the escape of magmatic gases which develop small cavities in the rock while the lava is solidifying. The gas bubble cavities, known as *vesicles,* are ideal channels for ground water if the lava is subsequently covered by later flows or sedimentary beds. Some of the largest ground-water reservoirs are buried vesicular lava flows.

Some rocks, such as granite, gneiss, quartzite, and dense limestone, lack any appreciable porosity and are therefore quite impermeable. In many cases, however, water can move through these rocks along joint cracks and fissures. A brittle rock may be so broken by joints that a considerable quantity of water is contained within the joint system.

Underground reservoirs of water have both upper and lower limits. Above the upper surface, or water table, is the *vadose zone* of percolating water which is wet during and immediately following a rain. This percolating water joins the water in the underground reservoir (*saturated zone*) and temporarily raises the level of the water table, which therefore undergoes considerable fluctuation. During the dry season it may sink many feet, and during a prolonged rainy season it may rise close to or even reach the surface. The water table in humid regions may never be more than a few feet below the surface, but in arid regions its depth may be several hundreds of feet. Unlike the water surface in a lake, the water table is not horizontal. It is a compromise in relief between the horizontal and the topography of the overlying land surface. Where the rocks are very permeable, as is loose sand, the water table approaches flatness. In less permeable rocks the gradient of the ground water surface is steeper. The relief of the water table, then, depends upon both the surface topography and the permeability of the reservoir rock.

The lower limit of ground water in homogeneous rocks is not as definite a plane as is the upper surface. Because of the weight of overlying material, rocks at great depths are more compact and have less permeability than rocks near the surface, but deep wells drilled to depths of over three miles have shown that sedimentary rocks continue to have sufficient porosity to carry water and oil even at those depths. The porosity undoubtedly diminishes downward, and eventually a depth is reached where the rocks are so compact that water storage is not possible. Where water is stored in joint cracks and fissures, as in igneous and metamorphic rock, the maximum depth at which water exists is considerably less. A number of mines troubled with ground water that pours into upper levels through rock fissures are dry at deep levels because of the gradual pinching together of the rock on opposite sides of the fissures.

Where the rock of the earth's crust is not homogeneous, but consists of alternating layers of pervious and impervious rock, ground water occurrence is quite different. The water is confined to the pervious layers, and the upper and lower limits of the ground water body are the upper and lower contacts of the reservoir rock. The water table concept is applicable under these circumstances only where the reservoir rock crops out. Then the upper level of water below the outcrop is the water table.

Composition and temperature of ground water. Ground waters vary greatly in chemical composition. Relatively pure (unmineralized) water is usually confined to the near-surface zone where a fresh increment of rain water is periodically received. However, rocks which consist of relatively insoluble minerals may contain fairly pure water to considerable depth. Examples are the waters which occur in sandstones formed above sea level and in fissures in igneous rocks. For practical purposes ground water may be classified as *hard* or *soft,* and *saline* or *nonsaline.* Hard waters contain magnesium and calcium compounds and, while potable, are not very satisfactory to use. Hard water requires an abnormal amount of soap to be effective in cleansing. It also tends to precipitate "scale" in pipes, tanks, and boilers, eventually so clogging or filling them that replacement becomes necessary. Soft water is either unmineralized water or water that contains none of the "hardening" compounds. It is so much more satisfactory than hard water for both domestic and industrial uses that many municipalities and even individual consumers either find a soft water supply or install artificial water softening equipment.

Saline waters contain enough dissolved sodium chloride to be salty to the taste, as well as other mineral salts. "Mineral waters" contain compounds other than salt in abundance. Iron, sulphur, carbon dioxide, and rarer substances may be present. Mineral waters are bottled in many places and sold for their alleged medicinal properties, but the therapeutic value of such water is often grossly exaggerated.

Connate water, magmatic water, and ground water of meteoric origin that circulate through rocks containing even slightly soluble minerals may become mineralized.

The temperature of ground water varies considerably from place to place. It tends, of course, to have the temperature of the enclosing rock; hence, the deeper the source of ground water, the warmer it is, for the average temperature of the rocks of the earth's crust increases downward about one Fahrenheit degree in every sixty feet. Because the rocks have approximately the same temperature the year round, water emerging from a shallow spring is relatively cool during the summer months and warmer than the average surface temperatures during the winter. But where artesian circulation carries water below the surface to a considerable depth, it may be much warmer than the normal temperature of the rock from which it eventually emerges. The heat of hot spring water results either from ground water coming in contact with igneous rocks that have not yet cooled to normal temperatures, or to the intermingling of ground water with magmatic water or steam.

MOVEMENT OF GROUND WATER

Ground water is capable of motion, but in many instances the movement is insignificant and, except in caves, it always moves very slowly. Water underground obeys the law of gravity just as does water at the surface, and it will flow down any slope that may be present. Surface water joining the ground water will follow the gradient or slope of the water table. Therefore, most movement takes place in the upper part of the ground water zone. The artificial removal of water by means of drilled or dug wells lowers the water table in the vicinity of the well, but as long as the water table stays above the bottom of the well, the water will move through the reservoir rock into the well. The speed of water movement underground depends upon the size of the pores, since the larger pores permit speedier movement because of less friction, and also upon the gradient of the water table. The down-valley movement of ground water in a river flood plain has been measured and found to be but a few feet a day.

While, of course, there is always a large body of water underground, the increment resulting from downward filtration of rain and surface water tends to be balanced by the escape of ground water through artificial and natural causes. In some areas so much water has been produced from wells that the water table has been lowered, and the volume of water stored underground materially diminished. The emergence of the water table at places of relatively low elevation permits ground water to escape and join surface run-off (Fig. 24). Where a valley cuts below the water table, ground water emerges into the valley through seeps and springs. In many instances the very bottom of the valley cuts the water table, and the water seeps directly into the river. Ground water also seeps into lakes and, in coastal areas, into the ocean. Where there is fairly uniform porosity of the rocks, the surface of the water in ponds, lakes, and streams marks the local elevation of the water table. A swampy area is produced where the water table intersects the land surface.

In addition to the methods of ground water escape just enumerated, there is some movement of water from a shallow ground water table to the surface by capillary movement. Ground water is also subject to direct evaporation into the air that fills the voids between the surface and the ground water table. Other methods of ground water loss are removal by plants through their roots, and chemical combination. Water unites with a number of compounds to form other

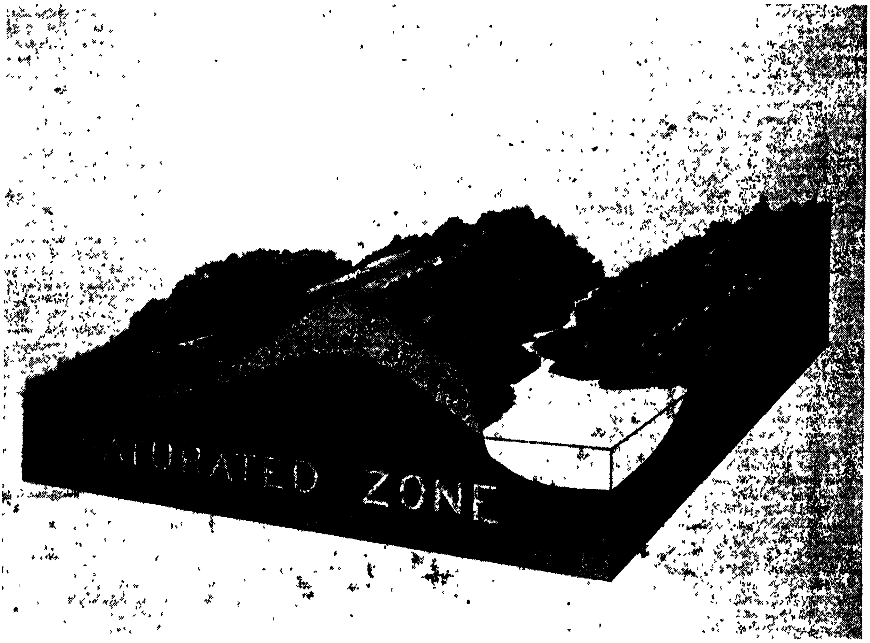

Fig. 24. Water table, or top of ground water saturated zone. Where the water table intersects the surface a swamp (left), or a lake (right), or a stream results. *By John Jesse Hayes.*

compounds by a process known as hydration. An example of this is the transformation of anhydrite ($CaSO_4$) to gypsum ($CaSO_4 \cdot 2H_2O$).

Springs. Most springs result from the emergence of the water table at the sides or bottom of a valley or at any other relatively low place. If the rock carrying the water is cavernous, like limestone which has been partially dissolved by ground water, the water may gush forth in great volume from a single opening. Where the rock is more consistently permeable, as a sandstone, conglomerate, or gravel bed, the ground water tends to seep out in many places. Some of the greatest springs in the United States occur where highly fractured and vesicular lavas outcrop along the walls of river canyons in Idaho.

Some natural springs are *artesian,* the water rising to the surface because of pressure or "head" rather than because of the emergence of the water table. An artesian circulation exists only where (1) a permeable rock, such as a sandstone, lies between or beneath rocks that are impervious, (2) the permeable rock crops out or otherwise

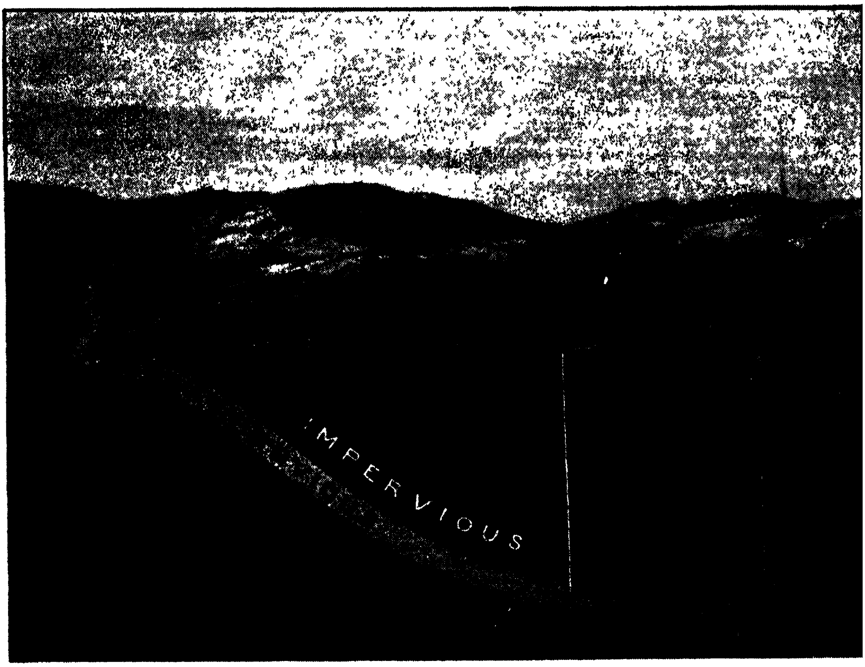

Fig. 25. Artesian water formation tapped by two drilled wells. The well at left is above the level to which pressure will force the water, so the water must be pumped through the uppermost few feet of casing. The well on the right is below the static or pressure level, so it is a flowing well. *By John Jesse Hayes.*

comes into contact with a supply of water at a relatively high elevation, and (3) water in the permeable bed has opportunity to escape to the surface where the surface lies at a lower elevation than the point of entrance of the water. Escape may be due either to outcropping of the permeable bed, or its penetration by a fracture or a fault (Chapter 11) that reaches the surface (Figs. 25 and 26). In some parts of the Rocky Mountains the sedimentary rocks form structural basins (basins formed by deformation of the rocks in the earth's crust). Permeable beds among these rocks receive water from rain and melting snow where they crop out high on the mountain flanks which form the rim of the basin, and this water runs down the sloping beds to an outlet at a lower elevation where it emerges under pressure.

In regions of recent igneous activity, springs result from upward movement of steam which carries with it ground water that it meets.

Most springs, especially the very large ones, discharge cold water. A part of the rain that falls on a region joins the ground water circulation and later emerges as a spring. It ordinarily does not go deep enough to reach temperatures much higher than the average temperature just beneath the surface. Furthermore, if the reservoir rock

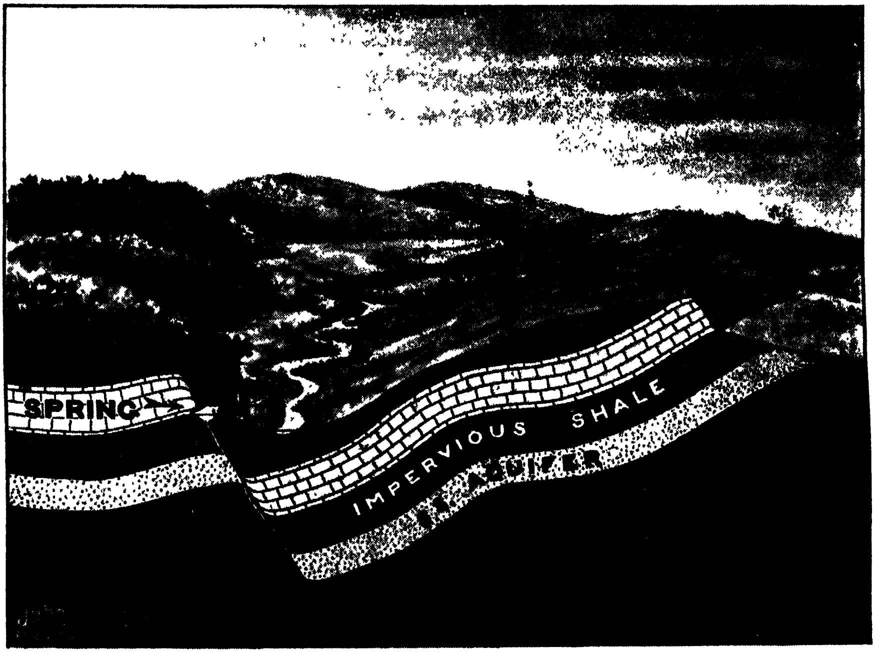

Fig. 26. Flowing spring at outcrop of fault fracture that taps sandstone (ss) artesian aquifer (water-bearing formation). *By John Jesse Hayes.*

is cavernous, the water moves at such a rate that it does not have time to adjust its temperature fully to that of the rocks through which it passes. Warm springs exist where the ground water has penetrated to considerable depth before rising to the surface. Some artesian waters are noticeably warm. *Hot springs* are confined to regions of fairly recent igneous activity where the rocks a short distance below the surface are abnormally hot (Fig. 27). Cooling following igneous intrusion is very slow because the overlying rocks function as a very effective insulator. The ground water that penetrates the hot rock zone naturally becomes hot. It may also become mixed with hot magmatic water. *Geysers* are a special type of hot spring in which flow or eruption is intermittent. The main essential is a tubular opening or conduit extending from the surface downward into consolidated but still hot lava. Inflowing water is heated above the boiling point, but is temporarily prevented from boiling by the weight of the overlying column of water. However, the water at some depth in the tube is eventually heated to the boiling point of water for that depth. The steam thus generated lifts the water above until it overflows, and this in turn reduces the pressure on the superheated

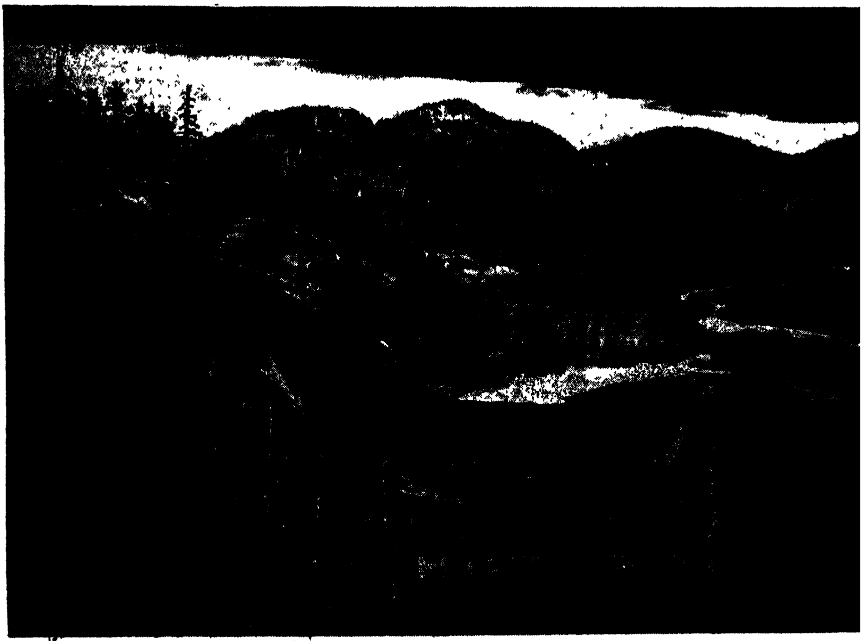

Fig. 27. Hot spring produced by natural artesian circulation through hot rocks.
By John Jesse Hayes.

water in the columns so that it bursts into steam and eruption occurs. After the eruption subsides the cycle starts anew.

Spring waters also can be classified as pure or mineralized. Pure spring water is rain water that has neither dissolved soluble minerals nor become contaminated by other waters in its travels underground. Mineralized spring water contains salts and other compounds in solution. The majority of so-called mineral springs owe their composition to the presence of salt, gypsum, and other relatively soluble minerals in the rocks through which the ground water has passed. However, some springs, especially those occurring in volcanic regions, contain much rarer compounds which are probably of igneous origin.

Springs vary in size from the small seepage used for water supply by the rural dweller to those which yield thousands of gallons a minute. There are several springs in the United States giving 500 second-feet or more of water. A second-foot is flowage of a cubic foot of water a second, or 448 gallons a minute. A spring yielding 500 second-feet of water would furnish 100 gallons a day to each individual in a city with a population of more than three million. Silver Spring in Florida is probably the largest limestone spring in the United States. "The water emerges through several openings into a basin an acre or more in extent and fully 35 feet deep, and gives rise to a navigable stream."[1] The stream that heads at this spring has a width of 110 feet, a maximum depth of 11 feet, and a velocity of over half a foot per second. The highest discharge reading for this spring is 822 second-feet. New York City, when its population was five and a half million, used about this amount of water.

Even larger springs issue from porous and fractured lava flows in Idaho. A series of these springs along a 50-mile stretch of Snake River between the towns of Milner and King Hill has an aggregate discharge of over 5,000 second-feet, adequate to supply more than one-fourth of the population of the United States. At most of the springs the water issues from the walls of the canyon at considerable heights above river level and drops in magnificent falls or cataracts to the river. Before the water was diverted for water power, Thousand Springs made a waterfall 2,000 feet long and 195 feet high. Other springs in this vicinity are also harnessed to develop electricity.

Yellowstone Park contains about 3,000 geysers and hot springs

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[1] Meinzer, Oscar E., Large springs in the United States: U. S. Geol. Survey Water Supply Paper 557, p. 12, 1927.

(Fig. 28). The total volume of water emerging at the surface through the orifices is enormous. However, the region is one of heavy precipitation, which accounts for the great volume of ground water. Nevertheless, there is evidence that some of the water (including steam) is of igneous origin. Hot springs are known in many other parts of the world, but geysers are found only in Yellowstone Park, Iceland, and New Zealand. One other hot-spring area in the United States, located near the center of the state of Arkansas, has been set aside as a National Park. This was the first area to be set aside by an act of Congress for recreational purposes. Although originally established in 1832, the reservation was not given National Park status until 1921. The hot springs are grouped at the base of Hot Springs Mountain, and their aggregate flow exceeds 850,000 gallons a day (a little less than one second-foot.) The water, which emerges through forty-six separate springs, is extensively used for curative purposes. Attractive bathhouses have been built on the reservation, and people come from all over the country for treatment. However, the mineral content of this water is very small, being considerably less than the water used in many municipal supplies. Other, more strongly mineralized

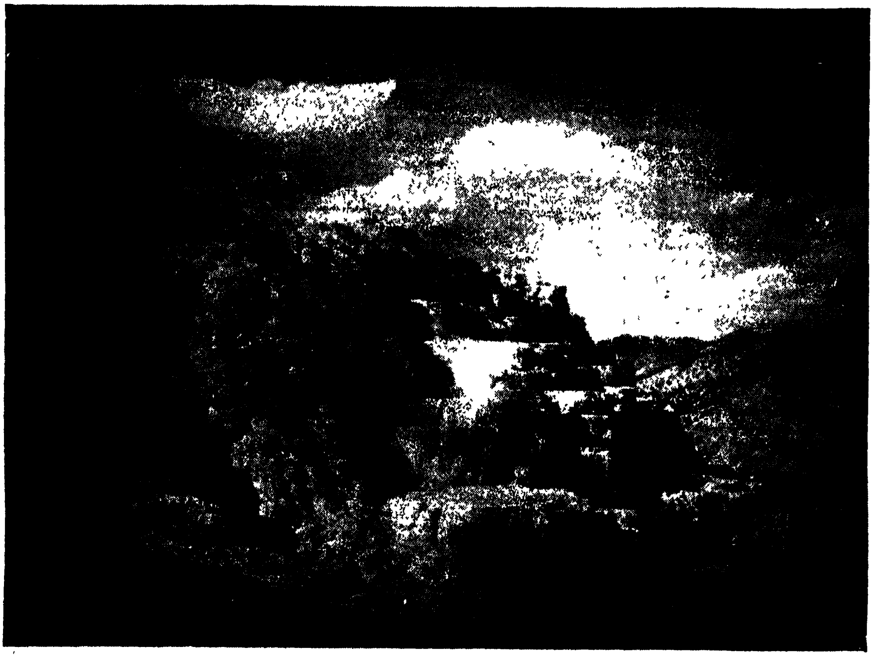

Fig. 28. Exceptionally large hot spring deposit. Jupiter Terrace, Mammoth Hot Springs, Yellowstone National Park. *Courtesy Union Pacific Railroad.*

springs are exploited for the alleged therapeutic properties of the water in many places, both in the United States and abroad. These serve as nuclei for health resorts and "spas."

WORK OF GROUND WATER

Ground water acts as both a dissolving and a depositing agent, but the volume of rock removed by solution is much greater than the volume of material deposited, so that the net effect of ground water activity is destructive. The destruction is rarely visible, as it is with wind, running water, and other agents of erosion, but it is nevertheless effective. As will be discussed more fully later, ground water also plays a passive role in "lubricating" soil and rock on the flanks of hills, causing landslides.

Solution. Pure water is not an effective solvent of any but the most soluble minerals, such as salt. However, most underground water already contains compounds in solution which greatly increase its solvent effect. Of these, one of the most active is carbon dioxide, a gas which, when dissolved in water, makes carbonic acid, a very effective solvent of limestone. Most of the carbon dioxide comes from soil bacteria, vegetation, and decaying organic matter. Other acids also may be present in ground water.

The most vulnerable rocks are salt and similar compounds which are deposited by evaporating seas or lakes. Gypsum and anhydrite, two forms of calcium sulphate, are dissolved not as readily as salt, but more readily than most other minerals. The solution of limestone is most prominent because of the widespread occurrence of this rock. Calcareous cement in sedimentary rocks is likewise vulnerable, and its solution by ground water causes the rock to disintegrate and return to its original incoherent condition. No minerals are entirely insoluble, and ground water, acting through geologic time, dissolves to some extent those which are ordinarily considered insoluble.

Deposition. Precipitation from ground water is caused in several ways. Very important, especially where ground water nears and reaches the surface, is evaporation. If the water is saturated with mineral salts, slight evaporation will cause their precipitation. A decrease in temperature also causes precipitation. Chemical reactions which take place between ground waters and rock minerals result in precipitation in some cases and in the replacement of pre-existing minerals with new minerals in other cases. Since carbon dioxide greatly increases the dissolving power of ground water, its loss will cause dissolved calcium carbonate to precipitate. Carbon dioxide is a gas and is held in water in appreciable amounts only when the water is under pressure. Release of pressure due to the movement of water to the surface or into a subterranean opening permits escape of carbon dioxide.

RESULTS OF GROUND WATER ACTIVITY

Solution by ground water creates openings in the rocks; precipitation produces spring and cave deposits and cements grains of sand or other material together.

Caves. One important phase of solution by ground water is the formation of pores in rocks at or near the surface. Like other methods of erosion, solution operates differentially, and the more soluble minerals are removed most rapidly. Therefore, a rock may first become pitted and later entirely dissolved.

Much more striking solution products are caves in beds of limestone, gypsum, and salt. Limestone caves are largely confined to a relatively shallow zone where the ground water contains much more dissolved carbon dioxide, necessary for the solution of limestone, than it does at greater depths. Furthermore, at shallow depths the pressure created by the weight of the rock lying between the soluble layer and the surface is not of such magnitude as to prevent the existence of cavernous openings. Caves are started by solution along the walls of joint cracks through which it travels, and eventually these openings are widened into caves (Fig. 29).

Some caves have been discovered through natural openings at the surface, or in the walls of ravines, and others in drilling for water and oil. For lack of any clues of their existence at the surface, more caves undoubtedly remain undiscovered than have been discovered so far.

About the only generalization which can be made in regard to the shapes of caves and caverns formed by ground water is that invariably they are extremely irregular. Tunnel-like openings broaden out into huge rooms, and then the walls pinch together so that further passage is difficult or even impossible. Some caves consist of a series of passageways, with intervening chambers and rooms which may or may not be interconnecting. Caverns are not always confined to one level, for rooms overlie deeper rooms, or caverns may end on one level and continue at an upper one. The deepest passageways usually contain streams into which all of the water entering the cave system collects. The irregularity of caverns is due to (1) the location of ground water channels, (2) the composition of the ground water, and (3) differential solution where parts of the rock are not equally soluble. The composition of ground water is important, for greatest solution will take place where the water first penetrates the soluble rocks, since it soon become saturated and can dissolve no more rock. The largest chambers mark places where the ground water first entered the soluble layers.

Caves have always fascinated people. They are visited by thousands each year because of their unique character and beauty and the opportunity they offer for exploration. Some of the outstanding cavern areas have been set aside by the Government as national monuments and parks for the use of the people. The following tables give the name and location of each of the federally owned cavern areas in the United States. All of these caves have been formed by ground waters, and most of them are located in massive beds of limestone. There are also many privately owned caverns exploited for use by the public, and countless more are not visited at all. The lime-

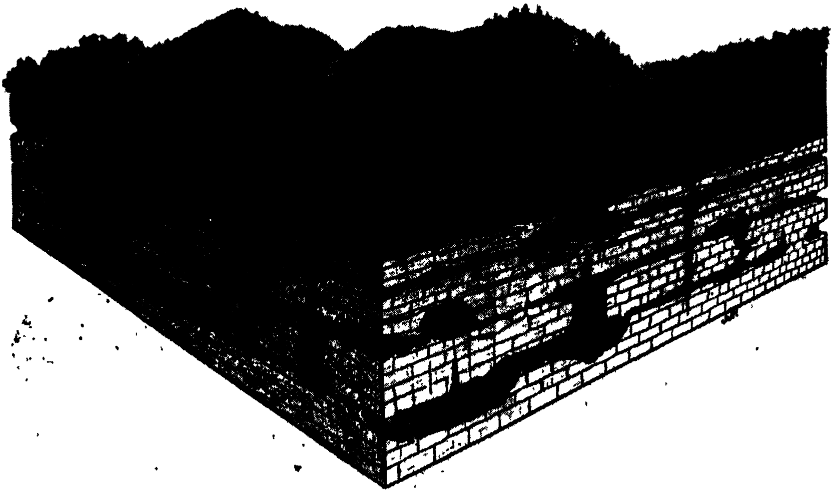

Fig. 29. Water percolating through fractures in limestone widened them here and there, producing caves. At right center, a cave roof has collapsed into a sink (Chapter 7). Later deposition of calcium carbonate produced the dripstone stalactite in lower center. *By John Jesse Hayes.*

stone terrains of Kentucky, Indiana, Ohio, Pennsylvania, and Virginia contain a large number of caverns.

NATIONAL PARKS

Name	*Location*
Carlsbad Caverns	New Mexico
Wind Cave	South Dakota
Mammoth Cave	Kentucky

NATIONAL MONUMENTS

Lewis and Clark Cavern	Montana
Shoshone Cavern	Wyoming
Jewel Cave	South Dakota
Oregon Cave	Oregon
Lehman Cave	Nevada
Timpanogos Cave	Utah

The Carlsbad Caverns constitute the largest series of underground caves yet explored. They lie about 26 miles southwest of the town of Carlsbad in southeastern New Mexico. The region is one of many caves dissolved by ground water from beds of limestone, salt and gypsum. The largest cavern is in limestone and extends diagonally downward to a depth of about one thousand feet.

> Formerly this cave was known as "Bat Cave," because of the thousands of bats that inhabit it. It is said that at dusk each evening these little mammals come out through a large natural opening, at times in such numbers that they look like smoke from a chimney, and for three hours pour forth in a steady stream; then in the early morning they return and with incredible swiftness fold their wings in midair and dart into the openings.
>
> Although several miles of underground passages have been explored, there are still many portions of Carlsbad Cave yet unknown; and its size is a matter of conjecture, although the National Geographic Society's expedition spent some six months at the cavern making detailed explorations. It consists of a series of lofty spacious chambers and connecting corridors, with alcoves extending off to the sides, that are of remarkable beauty, the limestone decorations excelling those in any cave heretofore described. One room, named the Big Room, is more than half a mile long, with a maximum width of 400 feet. The maximum measured height of the ceiling is 348 feet.[2]

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[2] *Glimpses of our National Monuments*, pp. 6, 7, National Park Service, Washington, 1926. Carlsbad Cavern was made a National Park in 1930.

Since the floor of the Big Room lies only about 700 feet below the surface of the ground, the rock between its ceiling and the surface is a relatively thin shell. The failure of the roof above caves produces *sinks* and some *natural bridges,* which are discussed in Chapter 7.

A few caves are dry, but many, including some of the largest ones, contain pools of water and even actual rivers. Where rain water can readily penetrate into the caverns, and the relief is such that the surface cuts into the cave formation in places, local run-off may be diverted so that it enters and passes through the caverns, eventually emerging at a lower elevation as a spring on the side or at the bottom of a stream valley.

> One of the best known underground streams is River Hall of the Mammoth Cave, Kentucky. It is but a portion of the great labyrinth of cavernous passageways, which constitute the lowest level of five successive series of galleries in this immense cavern. This great subterranean watercourse is the gathering bed of the rain waters, which enter the caverns largely through thousands of sink holes that open down from the surface.
>
> When Green River, the nearby surface stream, rises, River Hall becomes flooded, forming a vast continuous channel of water two miles long and varying from thirty to sixty feet in depth.[3]

Chemical erosion. Caves are visible evidences of erosion by ground water. In addition there is an enormous amount of destruction by ground water that is not ordinarily appreciated. About a third of the sediment that the rivers carry to the sea is in solution, and ground water was responsible for the greater part of it. Therefore, chemical erosion by ground water significantly decreases the volume of rock lying above sea level. In many instances, chemical erosion does not actually lower the surface elevation of the continents, but it does make the rock much more porous, so that the forces of physical erosion have appreciably less material to remove.

Mineral deposits. Up until less than a half century ago all ore deposits were thought to be of meteoric water origin. During recent decades evidence has gradually accumulated favoring origin by magmatic waters for these deposits, and economic geologists have altered their views accordingly. The origin of the important lead-zinc deposits of the Mississippi Valley, however, is still in dispute. The chief producing districts in this region at the present time are the Joplin or Tri-State district in southwestern Missouri, southeastern Kansas, and northeastern Oklahoma; and the southeastern Missouri district. Other deposits are mined or have been mined in Tennessee, Iowa, Illinois, and Wisconsin. The zinc and lead ores occur in irregular bodies in limestone.

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[3] Reeds, Chester A. "Rivers that Flow Underground," *Natural History,* 28, No. 2, 1928, pp. 136 and 137.

Economic geologists are in general accord in ascribing to ground water activity certain changes that have taken place in and adjacent to ore deposits. Copper ores exposed in the zone of oxidation change from copper sulphide to the soluble copper sulphate. This copper sulphate may spread through the ground water until the solution becomes so dilute that the copper is dissipated. However, if the ground water contains carbon dioxide or silica, the copper will be reprecipitated as a bright green or blue carbonate or silicate. Sometimes the waters bearing copper sulphate work downward through the vein to unoxidized sulphide minerals which reduce the copper sulphate and cause it to be reprecipitated as copper sulphide. In this way the primary ore body is enriched by ground water activity, a process known as *secondary enrichment*. Some of the richest copper ore bodies in the world owe their great concentration of copper to this process. Certain porphyritic igneous rocks (Chapter 10) in the Southwest contain disseminated primary copper sulphides, but the rock as a whole is too lean in copper to be exploited. However, secondary enrichment has so increased the copper content in parts of the rock that mining is profitable. These ore bodies are called "porphyry coppers."

Natural mineral borates, the source of commercial borax, are formed initially in volcanic sublimates and closely related deposits but may be dissolved by surface or ground waters and reprecipitated in workable deposits elsewhere. The first large-scale borax production in the United States came from Death Valley, California, where the borate minerals precipitated from capillary ground water that evaporates upon reaching the surface forming a crust over part of the valley floor.

Chemical erosion may cause insoluble minerals scattered through the rocks to become concentrated. Thick limestones in some localities contain scattered crystals of barite (barium sulphate), an insoluble compound. When subjected to chemical erosion by surface and ground water the limestone largely disappears and the once scattered barite becomes concentrated immediately above the underlying rock. It is mined and sold, mainly for use in pigments.

Hot spring deposits. Ground waters reaching the surface may deposit mineral compounds there. Outstanding examples of this are the spectacular terraces, cones, and other forms deposited around hot springs and geysers. The water flowing or erupting from these springs cools, evaporates, loses its dissolved carbon dioxide, and as a result precipitates the solids in solution. Calcium carbonate forms layers and crusts of *travertine,* and silica precipitates as *siliceous sinter.*

The limestone terraces at Mammoth Hot Springs in Yellowstone Park beautifully illustrate ground water deposition at the surface (Fig. 28). Precipitation there has been aided by microscopic plants known as algae which are responsible for the bright red, pink, and bluish-gray colors of the terraces where deposition is going on. Where deposition has ceased, the limestone is white. The hot water that has built the high terraces pours over them in a series of cascades. The slowly enlarging deposits have encroached upon a wooded area, engulfing large trees.

Veins, geodes, and dripstone. Ground waters precipitate minerals in fissures and cavities in rocks. A fissure filled with precipitated minerals is a *vein.* Although now almost all veins containing ore minerals are considered to be *hydrothermal* in origin (from hot waters from magmas), ground waters have deposited many veins of calcite, quartz, and even pyrite.

Cavities in rocks may become lined with crystals of quartz and other minerals by precipitation from ground water. Some of these crystal-lined cavities are round or egg-shaped and are called *geodes.* Other cavities that may become partially filled with minerals deposited by ground water are vesicular openings in lava flows.

Very beautiful ground water deposits are found in limestone caverns. The ground water entering such caves is saturated with calcium carbonate which tends to precipitate in the cave because of the escape of carbon dioxide from the water and the evaporation of the water. In one type of cave deposition a multitude of individual crystals, which line the walls and ceiling, appear like glistening diamonds when a light is thrown upon them. Another type is the *dripstone* (Fig. 30). Water seeping through the roof of a limestone cavern forms drops which hang pendant from the ceiling for a moment before falling to the floor. The pendant drop exposes the maximum water surface possible, evaporation is thereby accelerated, and precipitation of calcium carbonate takes place on the roof of the cave. Eventually an icicle-like deposit, known as a *stalactite,* is formed. The slightly shrunken drop that falls to the floor is immediately flattened

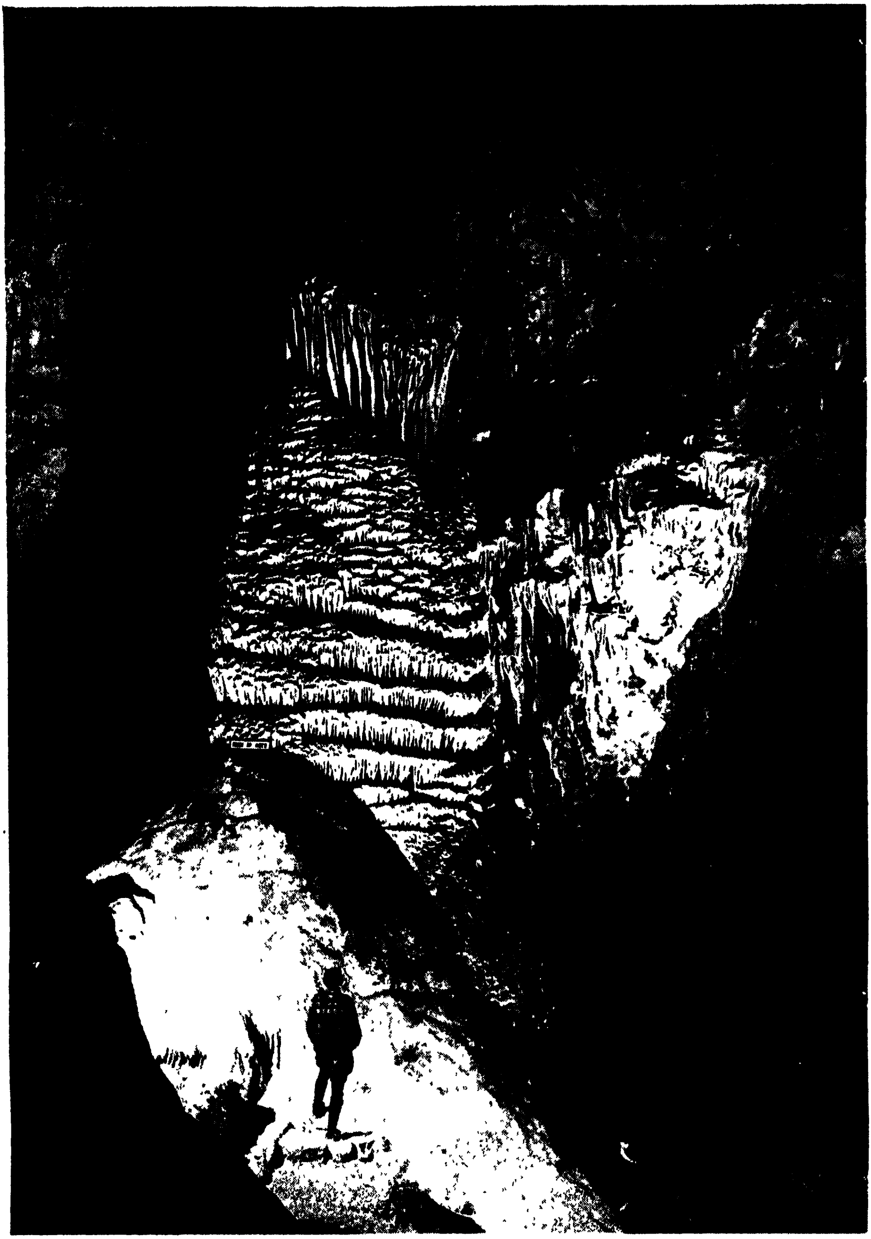

Fig. 30. The "Rock of Ages," a dripstone deposit in the Big Room at Carlsbad National Park. *By Kannicot and Grant. Courtesy National Park Service, U. S. Department of the Interior.*

so that further evaporation and precipitation take place. A reverse stalactite, known as a *stalagmite,* builds up from the floor. Eventually the stalactite and stalagmite may join to form a calcite *pillar.* Dripstone deposits exhibit many weird features. The glistening crystals, the white columns, needles, pendants, and pillars make such places a subterranean fairyland. A description of a room in the Carlsbad Caverns follows:

> Many places, like the Music Room, have formations resembling huge pipe organs, whose stalactites when tapped lightly give forth musical sounds. In yet other places the stalactites have grown together laterally, resembling curtains. Some of the curtains reach the floor, while others come but part way down, suggesting a stage curtain partially raised.[4]

Cementation. A less spectacular but geologically important type of ground water deposition is *cementation.* Sandstones and other clastic rocks hold together because ground water has precipitated minerals between the grains. The commonest mineral so deposited is calcite, but limonite and silica (quartz), are also precipitated as cement. It is fortunate that the cementation of a sedimentary rock is rarely complete, for the voids left empty are available for storage of water, oil, and gas.

An unusual type of cementation produces *concretions* (Fig. 31), tightly cemented bodies of rock which range in form from the spheroidal or discoidal to the highly irregular and often bizarre. In producing concretions, ground water first precipitates the cement at some nuclear point in the unconsolidated rock, and then cementation moves outward in all directions. A sphere results if the rock is homogeneous, but if there is greater permeability in one plane than another, the concretion tends to become discoidal. The nucleus for a concretion may be a leaf, a shell, some other type of fossil, or even an exceptionally large grain of sand. Rock City (Fig. 32), Kansas, is a striking example of the formation of concretions and their later erosion. Spherical concretions were formed by cementation of sandstone, and then, much later, rain wash, running water, and wind uncovered them. The concretions, because of greater resistance to erosion, have not been destroyed, while the enclosing uncemented sand has washed and blown away, freeing the spheres.

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[4] *Glimpses of Our National Monuments,* p. 8. *National Park Service,* 1926. Washington: Government Printing Office.

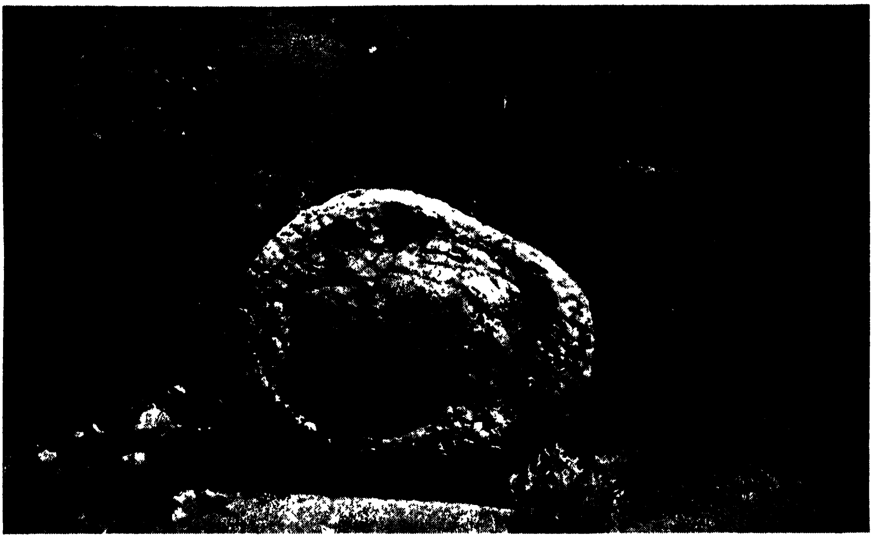

Fig. 31. Septarian concretion from Pierre shale near Cañon City, Colorado. "Septarian" refers to ramifying vein-filled cracks. *By R. C. Hussey.*

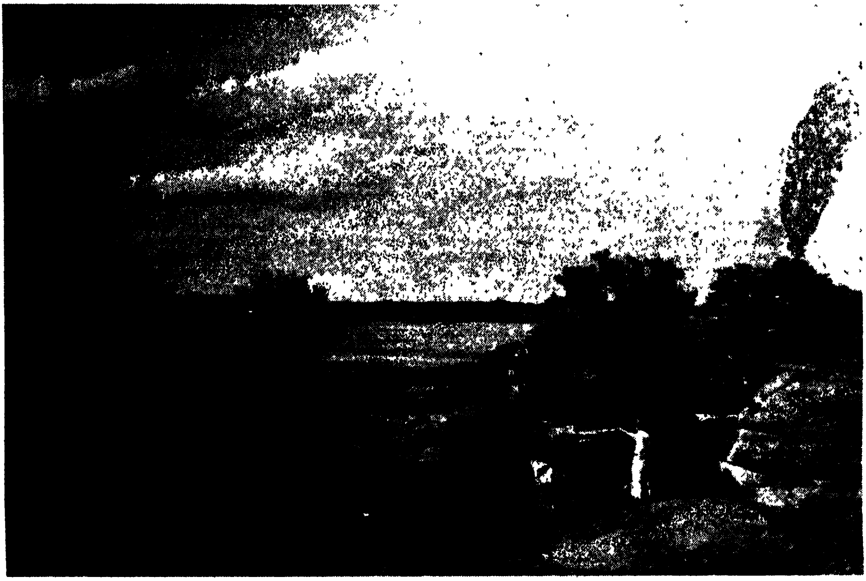

Fig. 32. Exceptionally large concretions that have weathered out from the enclosing sandstone. Rock City, near Minneapolis, Kansas. *By Oren Bingham. Courtesy Kansas Geological Survey.*

Replacement. Another type of ground water deposition is *replacement.* This involves dissolving one type of material and substituting something in its place. Ground waters are responsible for both the solution and deposition. The action goes on practically concurrently, and at any one time the volume of the replacing and replaced material is exceedingly minute. A familiar example of replacement is *petrifaction,* the replacement of wood or other organic material by silica. Petrifaction proceeds on such a minute scale that markings, such as the annular rings of a log, may not be destroyed, even though the woody tissue is entirely replaced. Examples of petrifaction are fairly common in parts of western United States. Petrified logs are scattered over an area of 100 square miles near Holbrook, Arizona, and of this the government's Park Service has set aside 40 square miles as the Petrified Forest National Monument. No standing petrified trunks or stumps are to be seen in this region, but they can be seen in smaller "forests" in Yellowstone National Park. Another type of replacement is *pyritization,* in which pyrite (an iron sulphide) replaces fossils or other minerals.

EXPLOITATION OF GROUND WATER SUPPLIES

Water is an essential mineral resource. Its availability has decided the location of homesteads, communities, cities, and industries. Deficiency of water supply has stifled the growth of some communities and has led others to spend vast sums in bringing in water from distant sources.

Water supplies may be classified into two types, surface and ground. Surface waters are used for domestic and industrial purposes, power, irrigation, and as a means of disposal of human and industrial wastes. The investigation and utilization of surface supplies is an engineering rather than a geological problem. However, water underground is a mineral resource as much as oil, coal, or gold, and both the study of its occurrence and the development of scientific methods of prospecting for it are functions of the geologist.

Prospecting for ground water supplies. From oldest times to the present many people have invoked magic when a supply of underground water was sought. Several methods of harnessing the supernatural to this very practical quest have been used. The most common of these is described in the following paragraph:

> When a farmer wants to sink a well, he usually casts about for a professional to tell him where to dig that he may be certain of strik-

> ing a vein of water at a moderate depth. Everybody, at least in rural communities, has heard of the practice of locating underground streams of water by means of a forked twig which, in the hands of a gifted carrier, points to such streams with unerring accuracy, and there are few communities that do not boast of at least one such practitioner. It is not so commonly known, however, that in earlier times the same means was employed to locate subterranean minerals and find lost or hidden articles, and even to discover and detect criminals. The twig is known in English as a "divining rod". . . . The person using it is often called a "dowser"; sometimes the terms water-witch and water-witching are used. In its most common form the divining rod is a forked twig or branch of apple or willow or hazel—presumably *witchhazel* would be most appropriate. With the rod in position, the dowser walks around over the land in which he is endeavoring to locate, say, a subterranean vein of water, and when he passes over such a vein the rod indicates the fact by turning in his hands and pointing downwards. Let the operator restore it to its upright position and again and again it will persist in turning and pointing downwards. If he moves away and the rod is temporarily quiescent, it again becomes agitated and turns down whenever he crosses the vein of water. . . . The disbeliever is inclined to ridicule the performance, but as a method of divining it is a real cult, and to its disciples it is no joke.[5]

Searching for supplies of ground water has become a specialized science in recent years, rather than a matter of faith and luck. A branch of the U. S. Geological Survey is engaged in a study of the ground waters of the United States, and specialists in this particular branch of geology, known as hydrologists, are employed on most major water-seeking projects. During the drought in 1934, several hundred geologists were employed in midwestern states to supervise the search for hitherto unknown sources of ground water, and this search was successful to a remarkable degree.

The procedure in ground water prospecting varies somewhat depending upon whether one is seeking a supply for a few individuals and perhaps some stock, or for a supply for a municipality, or an industrial plant. For a city supply, a water-bearing formation or *aquifer* capable of furnishing at least 50 gallons a day for every man, woman, and child residing in that city must be found.

Prospecting for water supplies in rock mantle is comparatively simple. If the bed rock is covered with rock mantle the elevation of the water table must be determined. It must be high enough to intersect the lower part of the rock mantle at some point in the area, or the mantle will be barren of water. The second step is to map by means of hand-augers or small power drills the elevation of the bed-rock surface in the apparently more favorable areas. Because water flows downhill whether it is on the surface or underground, the subsurface movement of water in the mantle is toward the lowest points on the bed-rock surface. An ideal condition for abundant underground water is a valley in the bed-rock surface which has been filled with rock mantle, for rain water after percolating downward to the bed-rock surface will move in the direction in which that surface slopes and accumulate in the lowest places.

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[5] Hering, Daniel W. *Foibles and Fallacies of Science,* pp. 126-128. New York: D. Van Nostrand Company, Inc., 1924.

In prospecting flood-plain alluvium, whether built by a still existent stream or by some river that has disappeared, a series of holes is usually drilled from surface to bed rock across the valley to find porous water-bearing zones. The widest, thickest, and deepest zones will have the greatest yield of water, provided that the permeabilities are approximately equal.

Once the site for the well has been chosen, it should be dug or drilled to a depth several feet below the water table, for the water table fluctuates with the seasons and it is essential to have the bottom of the well below its lowest level. Also, the pumping of a well makes a local conical depression in the water table. The deeper the bottom of a well, the steeper will be the flanks of the cone and the faster will the water move into the well.

The technique involved in prospecting for water in stratified rocks is somewhat similar to that used in the search for oil. The first step is to determine the stratigraphic section or series of rocks present in the district, paying particular attention to the beds that might be aquifers. This study can be made from surface observations in regions where topography or folding gives a thick series of rock outcrops. In most cases, however, surface observations are not enough, and the stratigraphic section has to be prepared through a study of logs (record of rocks drilled, with depths) and cuttings of wells drilled in and near the region for oil, gas, or water. These data give not only the depth of the aquifiers at various places, but also their thicknesses, permeabilities (if samples are available), an estimate of the amount of water available, and perhaps some information as to its quality.

The second step is the mapping of the structure or inclination of the buried strata, to determine the depths of the aquifers in all parts of the region under investigation.

Next comes the drilling or digging of a well at a recommended site. Unfortunately, some wells fail to yield the desired volume or quality of water. Sandstones are likely to be lenticular (lens-shaped), and the aquifer sought for may disappear between the nearest point of information and the site of the test well. Also, the degree of cementation of a sandstone varies from place to place, hence the aquifer pierced by the test well may be so tightly cemented that it will not yield sufficient water. In some cases the water, though quite abundant, may be too highly mineralized for use. Even in what is apparently the same aquifer, water may change in a few miles from fresh to salt. Lastly, the aquifer, although yielding water, may not be replenished at a sufficiently rapid rate and in consequence the yield after a time will gradually diminish.

Use and misuse of ground water supplies. The uses of ground water are essentially the same as for surface water. Ground water is extensively used in upland areas where surface supplies are not available. The thousands of windmills scattered over the prairies and plains of the central and western parts of the United States attest to the great use of ground water by town and country dwellers. A large number of municipalities also use ground water obtained either from flood-plain sands or from deeper bed-rock aquifers. Deep sandstones are tapped for water supplies in such states as Missouri, Iowa, Illinois, and Wisconsin, but to the southwest in Kansas and Oklahoma the water in rocks of equivalent age is too highly mineralized for use even by stock.

Water that is merely hard can be successfully treated. The only water available in many parts of the United States is hard, and its use causes much trouble and expense. Special soap may be used, although the average citizen merely uses larger quantities of standard brands. Also the dissolved minerals tend to precipitate in pipes, tanks, and boilers. Many industries that cannot use hard water either have to be located where soft water is available or must install softening equipment where hard water is used. Many municipalities have installed plants to soften water and the taxpayers have found that their savings in soap purchases alone have exceeded the taxes levied to operate and amortize the plant.

Ground water is used for irrigation in many districts, but not as extensively as surface water. Where the depths to water do not exceed 50 feet, it has been found feasible to pump ground water and thereby convert grazing or grain land with a relatively low yield per acre into truck and fruit farms.

The people of the United States are beginning to realize that ground water is a great natural resource that should be conserved. Originally it was believed that ground water, if present at all, was inexhaustible. The farmers who pumped water from beneath the Great Plains for stock and irrigation were told that the water came from the melting snows of the Rocky Mountains and that the supply was everlasting. Drilling for both water and oil in the Great Plains area has subsequently altered this concept. The great sand and sandstone bodies that carry water in this region are not continuous and therefore cannot function as a pipe line from the Front Range of the Rockies to city or farm wells on the Great Plains. Additional evidence is given by records made of the pressures in wells in this region. Many wells when drilled struck water under such head that they flowed; but now they have to be pumped. Other wells in which the pressure forced the water close to the surface now have to be pumped from much deeper levels. Obviously, water is being removed faster than it is entering these aquifers. Some of the sandstones may not have any connection with the surface and hence have little opportunity for replenishing their supply. In this case the buried reservoir is slowly but surely being emptied. The volume of water that may be stored in a large body of sandstone is enormous, so complete exhaustion takes several decades. For example, a 50-foot bed of sandstone with a porosity of 20 per cent, when filled with water is equivalent to a lake 10 feet deep. In every square mile of such a sandstone, enough water is stored to give over 50 gallons of water a day for a year to each individual in a community with a population of 100,000.

Unless protective measures are taken, the outlook is rather gloomy for parts of the northern Great Plains region where ground waters are the sole supply at present, and these waters are being withdrawn faster than the aquifers are being recharged. More use will have to be made of surface supplies where available in order to diminish somewhat the amount of water being withdrawn from the ground. Of much greater importance, however, would be the institution of a program of recharging the aquifers through diversion of surface water. This could be done by means of wells drilled to the aquifer into which water would be directed that would otherwise evaporate or escape down the valleys to the sea. Recharging is already being practiced in parts of California where the natural reservoirs are deposits of valley alluvium.

It is likewise of utmost importance that pollution of fresh ground water by oil-field brines and industrial wastes be prevented. Due to the slow rate of travel of water underground, such pollution may be very insidious. Its effects may not be noticed until years after the pollution takes place. Most oil wells produce brine as well as oil, and the brine is separated from the oil and disposed of at the surface near the well. Disposal by means of evaporating ponds is attempted in many cases, but most of the brine filters down into the soil and contaminates the ground water. Oil wells that are poorly cased permit the rising in the well of deep brines under artesian head, which enter into and pollute higher fresh-water aquifers. The same thing happens when wells are abandoned and improperly plugged. The ground water in entire counties in Kansas and Oklahoma has become unfit for use through contamination by brines which originated in deeper formations but which were allowed to seep into the shallower formations during the exploration and development of oil and gas fields. Although it is too late to do anything about the areas already polluted, abatement is quite possible in regions undergoing development today. Abandoned wells should be properly plugged, and the brine produced with oil either evaporated in leak-proof ponds or returned, by means of disposal wells, into deep salt-water bearing formations, preferably into the formation from which it came.

CHAPTER 5

Running Water

RUNNING WATER IS THE PRINCIPAL EARTH-transporting medium. The rivers of the world are ceaselessly at work carrying material from the lands to the sea. Given time enough, the continents and islands would be eroded below sea level by the combined action of all the erosive agents.

Running water produces our most familiar topographic features, such as valleys and the intervening ridges, hills, and mountains. At the bottom of most valleys are plains, which are extensively utilized for farming, townsites, and routes of travel. Running water can be a very spectacular geologic agent; a stream in flood may noticeably change the local topography in a very few hours.

SOURCE OF WATER

Practically all the water running on the surface of the land has at one time fallen from the atmosphere; a minor portion is added by volcanic eruptions which bring some water from the deep interior. The water which falls onto the earth as precipitation is a part of an endless cycle. It came from the clouds, which are formed by condensation of water vapor in the cooler temperatures of the upper air, and the water vapor was derived by evaporation from the earth's surface. Naturally, evaporation is greatest from the oceans, which cover three-fourths of the globe, but water is constantly being evaporated also from rivers, lakes, swamps, plants, from the soil and rocks, and from snow and ice.

Precipitation falls as rain, snow, sleet, or hail. Part of the rain water runs off immediately into the various river systems of the earth. Snow, however, stores water until thawing takes place, which may not be until the following spring or summer. Consequently many rivers draining mountainous areas reach their maximum volumes during the summer months. Not all of the snow falling at high altitudes and in high latitudes thaws; some of it is converted into ice, part of which form glaciers. Glaciers move into warmer zones, and their margins reach levels where thawing occurs. Rivers that have their headwaters in mountain valleys containing glaciers obtain most of their water from melting ice.

Precipitation upon reaching the earth's surface follows three paths. Some of it evaporates, some enters the soil and becomes ground water, and the remainder joins the surface *run-off*. The percentage of water that evaporates depends upon the temperature, humidity, wind, and surface conditions. Other things being equal, the higher the temperature and the lower the humidity, the greater the amount of evaporation. However, evaporation also takes place from snow and ice surfaces, and it is possible for a snow or ice field to be completely dissipated in this manner even though the temperature never rises sufficiently high for thawing. Humidity is the amount of moisture in the air. If the air is already saturated above a given area, it cannot acquire further water vapor by evaporation. The wind plays a vital part in evaporation. If the air is quiet, water-saturated atmosphere may overlie areas of potential evaporation without adding to its moisture content, but if the air is moving so that unsaturated atmosphere is constantly brought in, evaporation occurs. Evaporation takes place in arid regions even while rain is falling, and, in extreme cases, rain which starts from the clouds may be completely evaporated in the lower air before reaching the ground.

Several factors control the fate of water after it falls on the surface. The prime control is topographic slope, for the greater the slope the faster the water runs off; hence a minimum amount remains to be evaporated or to sink below the surface. Vegetation is a second control of almost equal consequence. Who has not taken shelter under a tree during a rain? Such shelter is effective until every surface overhead has been coated with a film of water, and some leaves, by their shape and position, may hold tiny pools of water. Much of the water falls to the ground when the leaves are shaken by the wind, but, even then, it reaches the ground less violently and in smaller quantity than if no trees were present. Water films coat not only the trunks, branches, and leaves or needles of trees, but also the surfaces of bushes, flowers, and blades of grass. Much of this water is evaporated

Furthermore, vegetation retards the rate of runoff, an effect much greater on gentle than on steep slopes. Water checked in its downhill rush on moderate slopes by growing and fallen vegetation is available for evaporation and downward seepage into the soil and rock. Vegetation also increases the thickness of the porous soil zone by adding layers of organic debris.

We have only recently begun to appreciate the role of vegetation in controlling runoff. Many parts of the country during the last few decades have suffered from excessive soil erosion, gullying, floods, and other disastrous effects of abnormal runoff caused by cultivation, overgrazing, and deforestation.

Another factor affecting the runoff is the character of soil or rock at the surface. Sandy soil permits much more water to percolate through it than does clay soil. Fractured limestone is more pervious than unfractured shale. Vesicular lava furnishes more numerous channels for water than most other rock.

Runoff is also controlled by the rate of rainfall. A heavy rain will soon fill the open spaces immediately below the surface, so that further addition is impossible until the water in these pores empties into lower openings. Therefore, two inches of rain falling in one hour contributes more to the runoff than two inches falling over a ten-hour period; the farmer recognizes this fact by referring to the for mer as a "gulley washer" and to the latter as a "ground soaker."

A major source of runoff is ground water. Where hillsides and valley walls intersect the water table, ground water emerges as seeps or springs and becomes surface water. In humid regions this is a steady supply if the rainfall be distributed rather evenly through the year. Where considerable seasonal variation in rainfall occurs, the water table may fluctuate to such an extent that it lies above topographically low points during and following the rainy season and contributes to the runoff, but, during the dry season, it sinks below the land surface at all points so that all seepage or flowage onto the surface ceases.

COURSE OF THE RUNOFF

Runoff, regardless of whether it originates from local precipitation or ground water, moves downhill, collecting into streamlets which join to form larger streams. The streams follow depressions which they have carved out or which have been formed in other ways. Streams are either *intermittent* or *permanent*. An intermittent stream of the year when the water table is high. It also carries surface runoff following a rain, but this supply is short-lived. Permanent streams are steadily fed by water escaping from the ground-water supply. Most streams are intermittent near their headwaters and permanent farther down, but a mountain stream fed by melting snow and ice may be permanent even at headwaters. Some streams, rising in a mountainous area, flow into an arid region with low water table and lose part or all of their water in the unsaturated debris below the stream bed. The nature of the floor over which the water passes determines to a considerable extent the amount of the loss. If the stream bed is covered with gravel, sand, or other porous materials, all of the water may disappear. A tight clay floor, on the other hand, prevents much seepage into the ground; hence the principal loss is by evaporation.

A river, its tributaries, and subtributaries constitutes a *river system,* and the area drained by a river system is its *drainage basin.* A map of the basin showing the river with its many branches displays the *drainage pattern* of the river system. The complexity of this pattern depends upon climate, vegetation, character and structure of rocks, and age of stream. A well developed drainage pattern, in a region where the surface materials are approximately alike in their resistance to erosion, branches like a tree and is called *dendritic.*

PROCESSES

Erosion. To erode means literally to "gnaw off." It is a term used by geologists to include transportation of weathered rock, abrasion of the fragments by contact with each other, abrasion of bedrock over which the fragments move, and solution of soluble materials. Erosion by running water has two principal phases. One of these is the wearing down of interstream areas by *sheet wash;* that is, by surface runoff before it becomes concentrated in a channel. A sheet of rain water running down a sloping surface will pick up and transport small particles in its path, as a rain storm will remove dust from a roof.

The second phase of erosion by running water is the development of the valley by streams. Once the runoff water becomes concentrated in a stream, no matter how small, *valley cutting* begins. This is one of the most important geological activities; much of the land above sea level exhibits a complex of valleys that have been eroded into it. (The ability of a stream to erode its channel is dependent to a large extent upon the speed or velocity at which the water moves. Velocity in turn is determined by a number of factors of which the most significant is the slope or gradient of the stream bed. A river having a steep gradient moves much faster than one flowing over a more gradual slope, and its potential capacity for work is much greater. The cross-section of the river channel also governs the velocity to some extent. Other things being equal, a given volume of water running down a narrow channel will move faster than when spread over a wide channel. Water, like any other moving substance, is retarded by friction and the greatest velocity prevails where water has a minimum area of contact with the bottom and sides of the channel.

River velocity is also controlled by volume of water. As the volume increases, the frictional resistance per unit quantity of water decreases. The water moves faster. Furthermore, local increase in volume produces a steeper slope downstream at the water surface, greatly accelerating the rate of flow. In many river systems increase in velocity resulting from increase in volume between headwaters and mouth is more than offset by a decrease in gradient, so that the water does not move as fast near the mouth as it does near the source. The importance of volume in controlling velocity can be observed best by watching a river at one point through seasonal variations in flow. The velocity of a sluggish stream often increases to such an extent during high water that the stream does great damage to its banks and to property located within reach of the flood waters.

The load of sediment carried by a river also affects the velocity, since particles sinking toward the bottom retard movement of the water. Also the sediment dragged along the floor and sides of the channel increases the frictional resistance.

Lastly, the character of the floor over which the river passes exercises some control over the stream's velocity. A smooth rock floor will offer less frictional resistance than a rough channel or one clogged with rock debris or vegetation.

Channel cutting involves two separate processes. One is hydraulic action, or the impact of water, which flushes unconsolidated material or weak rock downstream. The other process is abrasion, or the wearing away of rock by sediment which the stream carries. A clear stream is not able to abrade effectively, but a stream carrying sediment "sandpapers" the rock over which it passes. Therefore, water running over resistant rock must have tools with which to work if it is effectively to erode that rock. The proportion of a river channel where bed rock is exposed is relatively small, for, in most places, the bedrock is covered by stream-deposited alluvium. Stream abrasion takes place principally during floods, when the velocity is so great that all of the load is in motion.

The debris at a given point on the floor of a river channel has been obtained in several ways. It may be a product of the weathering of underlying rock; it may have been brought by the river during periods of high water; or it may have been brought in by tributary streams. Where a river flows through a steep-walled valley, a large amount of debris is added from the *creep, slide,* and *fall* of loose rock from above. A relatively small amount of material also may be obtained by the down-cutting of the stream.

Streams cut into their banks, especially at bends where the fastest current flows along the outer bank. This is known as *lateral erosion* or *planation.* When the bank is sufficiently undercut, the unsupported rock above falls into the stream and the valley is widened by that amount. One type of natural bridge has been produced in this manner (Fig. 33).

Not all stream erosion is physical. River water dissolves relatively

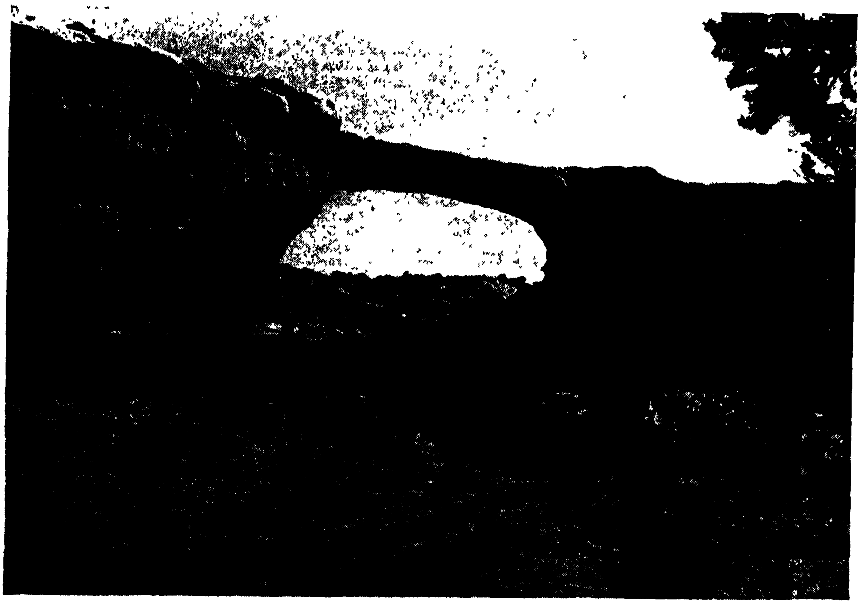

Fig. 33. Natural bridge resulting from lateral erosion by an intrenched meandering stream. Owachomo Natural Bridge, San Juan County, Utah. The rock is a Permian sandstone. *By A. J. Eardley.*

soluble rocks, such as limestone, dolomite, and gypsum, as it flows across them. Sandstone cemented by calcium carbonate may have the cement dissolved so that the rock disintegrates and loose sand is made available for removal. A great volume of material is carried by the rivers to the sea in solution, but most of this material was dissolved in ground water which later joined the surface runoff.

Transportation. Removal of rock debris and other material is an essential part of the erosive process. Rivers carry an almost unbelievable volume of sediment into the ocean every day, as has been shown by analyses of water sampled at river mouths. In the United States alone, more than 500 freight trains, each consisting of 100 cars and making one round trip a day, would be required to carry the material that is transported by the rivers from the uplands to the sea.

Although some of the material carried by streams is obtained by abrasion, most of it is weathered material already available. Even mountain torrents have more loose material available in their channels than they can carry away. *Weathering not only keeps up with the agents of removal but is usually far ahead of them.* Some of the material that slides and rolls into the channel of a stream is too coarse for the water to move. Weathering and abrasion break it down into smaller and smaller pieces until movable fragments are produced.

The volume of load that can be carried by a stream is a function of the velocity and volume of the water. Increase in velocity and increase in volume augment the amount of load that a stream can carry. Volume increase is invariably accompanied by increased velocity, as explained earlier; hence the load carried by a stream is multiplied many times when it is in flood.

Material is transported by rolling, sliding, saltation, suspension, and solution. The debris *rolled* along river beds ranges from large boulders to small grains of sand or clay depending upon the velocity of the water and the size of available particles. A river in flood can roll material down its bed that is far too heavy for it to handle during normal flow. Consequently, the coarser fragments travel downstream in a series of moves. Rolling on the river bottom causes considerable wear, hence boulders and smaller particles transported in this manner decrease in size and become well rounded.

Water pushing against angular fragments may cause them to *slide* instead of roll. *Saltation* is movement in a series of jumps; rock particles are alternately picked up and dropped by the stream currents, but each time such particles are lifted off the bottom they are carried downstream.

Many turbulent mountain tributaries dump boulders of such magnitude into the main river that the latter, because of lower gradient and lesser velocity, cannot move them except in times of flood.

The intermittent march of sediment to the sea is especially observable in the case of sand. Operators of dredges obtaining sand from river channels report that the supply is replenished by each flood.

Material in *suspension* is neither floating at the top of the water nor being dragged along the bottom, but is "suspended" between. Sediment is heavier than water and has a constant tendency to settle out, but it does not sink straight down, because of the current. It settles in a sloping direction, the angle of the slope depending upon the shape of the particle, its weight, and the velocity of the water. Very flat mineral grains, such as scales of mica, offer more resistance to fall in water than spherical grains, and therefore sink very slowly. Gold, because of its weight (specific gravity), tends to sink rapidly and at a steep angle. The greater the velocity of the water the gentler the slope followed by a particle in sinking.

However, in spite of its tendency to settle to the bottom, sediment may remain in suspension in a river for the entire distance to the sea, for upward currents caused by deflections of the river current as it passes over obstructions in the channel keep boosting the particles. The unevenness on the floor may be due to inequalities in the bed rock if the channel is cut through solid rock, but it is usually due to the presence of boulders, cobbles, and pebbles in the stream bed.

Suspended material also may travel by stages because a river can carry much more sediment in suspension when in flood than during times of normal flow. Between floods this surplus load rests on the bed of the stream.

The size of fragments varies greatly between headwaters and mouth of a stream. Tributaries of the Mississippi River near their headwaters in the Rocky Mountains roll boulders two or three feet in diameter, or even larger, down the bed of the stream at times of high water. The size of the sediment decreases downstream so that, at the mouth of the Mississippi, the material being carried, even in times of flood, consists mainly of fine particles of silt and clay. Differences in velocity account for the great difference. The headwater streams, in spite of their relatively small volume, flow over steep slopes and have much higher velocities than has the Mississippi River, with its average gradient of less than eight inches per mile. The typical river gradient, when plotted on paper, is a smooth curve which is steep at the source and levels off toward the mouth. Actually the floor of the channel is a succession of stretches of different gradients.

Quite distinct from the material that travels by rolling and suspension is the load in *solution.* About a third of the total amount of material that the rivers daily carry to the sea is in solution. The dissolved material travels without stopping.

Although rivers carry millions of tons of dissolved materials in solution, rarely is the concentration sufficient to affect the taste of the water. However, a few rivers that drain salt-bearing rocks are noticeably salty. River water throughout the Mississippi Valley area is very "hard" because of the presence of calcium carbonate (dissolved from limestones) and other compounds.

Deposition. The final step in the work of running water is the deposition of the material that it carries. Deposition results principally from decrease in velocity caused by (1) decrease in gradient as the river proceeds toward its mouth, (2) decrease in volume of water, or (3) increase in load. Abrupt changes in gradient take place principally where a stream emerges from a mountainous region onto a plain, or where it flows into a lake. Less abrupt but nevertheless effective changes in gradient take place as the mouth of a river is approached. The lower end of a river may have attained base level, in which case further downward erosion is negligible, and deposition takes place. Changes in gradient along the course of a stream have an immediate control over river velocity and consequently an important effect upon deposition.

Many rivers increase in volume consistently between headwaters and mouth because of the influx of water from tributary streams and also, in many instances, due to greater rainfall nearer the coast. In such cases, there will be no deposition that is due to decrease in velocity through loss in volume. However, there are streams that do suffer a loss in volume between their mountainous and well watered headwaters and their mouths because they pass through an arid or semiarid zone where there is greatly increased evaporation and a depressed water table that permits the escape of river water into the soil and rock. Many streams in these circumstances, like the Arkansas in Colorado and Kansas and the Platte in Colorado and Nebraska crossing the Great Plains of the United States, are choked with sediment between the Rocky Mountain front and the more humid areas of the Mississippi Valley because of lessening of volume.

The load of a river often is increased through the addition of sediment carried by a tributary. The tributary stream may have relatively small volume but so high a velocity that it transports a heavy load of sediment. In spite of the greater volume of the main river, its lesser gradient may not give the water sufficient velocity to move the added sediment, and deposition takes place. The material will be dropped immediately below the mouth of the tributary.

Deposition also takes place in lakes that exist within the drainage basin of a river; and voluminous deposition, forming deltas, occurs where streams enter the ocean.

RESULTS OF EROSION BY RUNNING WATER

Valley development. A valley is an elongate depression with a continuous, but not necessarily consistent, slope in one direction. It is occupied by either an intermittent or a permanent stream. Valleys were once considered cracks which opened up suddenly in the earth's crust, but now we realize that they have been carved by the streams flowing through them. Who has not seen a gully formed in loose soil by the runoff from a single heavy downpour? This is an example of valley forming, though on a small scale and at an unusually rapid rate.

Valley development begins when runoff becomes concentrated on the surface. The resulting streamlet or rill carves a gully which in time may become a ravine, and the ravine may eventually be enlarged into a large valley. While valley growth at any point goes through these stages, the valley is also lengthening by extending itself headward through continual cutting back at the source. This is known as *headward erosion.*

Valley growth is accomplished by both downward and lateral erosion. Downward erosion is the vertical cutting done by the stream itself. Although in most cases downward erosion appears to dominate in the carving of a valley, actually it has caused the removal of a relatively narrow belt of material lying between the bed of the present stream and the original surface. The rest has been removed by lateral erosion. Bends in the course of a stream are always present, and where the current swings against a bank it erodes laterally. The greatest lateral erosion is not done exactly at right angles to the direction of a valley, for the current sweeping around a bend is strongest against the bank slightly downstream from the outermost point on the bend. For this reason the bends tend to migrate downstream, eroding the sides of the valley in the course of the migration.

Other agents, besides lateral erosion by the river, are at work in widening a valley. Gravity fall or creep and sheet wash contribute by moving loose material down the sides of the valley toward the bottom. As downward cutting of a stream destroys the equilibrium of the material composing the valley wall, there is a constant tendency for this material to creep, slide, and even roll down to the valley bottom. Some debris is blown away by the wind.

When a valley floor has been cut so low that the stream has only enough slope to maintain its flow to its mouth, the stream is said to have reached *grade*. From that time, vertical erosion is of little consequence, while lateral erosion becomes even more important than before. Therefore the valley is no longer deepened to any extent but may be very considerably widened. The stream develops extensive flood plains on which it meanders. The meander bends enable the stream to widen the valley by lateral erosion or *planation* in a manner similar to that of a twisting, downcutting stream as described in a preceding paragraph.

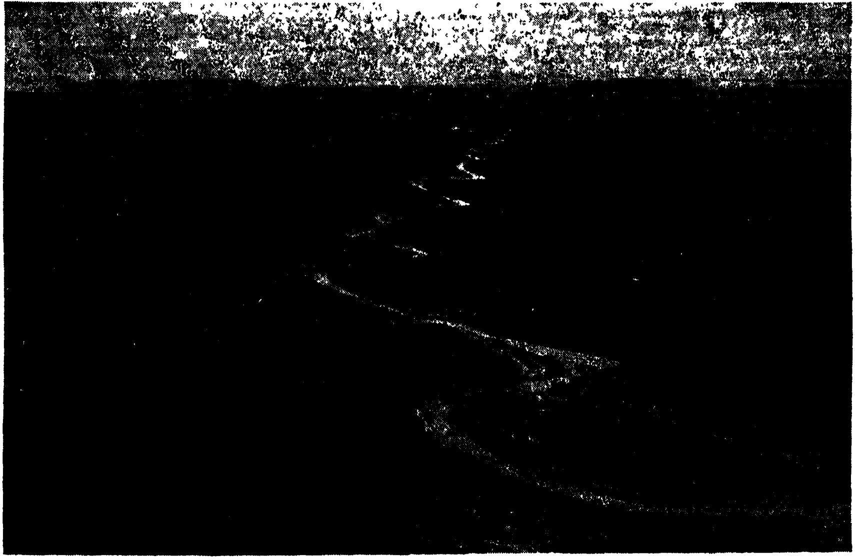

Fig. 34. Lateral erosion on outside of meanders. Low hills in foreground are being undercut and destroyed by meandering river. Rio Puerco, west of Albuquerque, New Mexico. *By permission Spence Air Photos.*

Waterfalls. Water that is moving relatively fast, usually because of constriction in the channel, makes *rapids.* If the water proceeds in a series of low falls these are known as *cascades,* and a single vertical drop is called a *waterfall.* Falls are formed in several ways. Tributary streams may enter the main valley by a series of falls where erosion, either by running water or ice, has deepened the main valley to a greater extent than the tributary valley. Most falls, however, are due to the passing of the channel from resistant rock to rock that is relatively soft. As the weaker rock is cut deeper, the water falls over the edge of the resistant rock. If the strata are flat-lying, the water pounding on the weaker rock at the foot of the falls undercuts the resistant top ledge so that it gradually crumbles at the lip of the falls. As time goes on, waterfalls of this type recede; that is, they move up the valley. The same process takes place if the strata are tilted so that they dip in an upstream direction. In the latter case, however, the recession is accompanied by a gradual low-

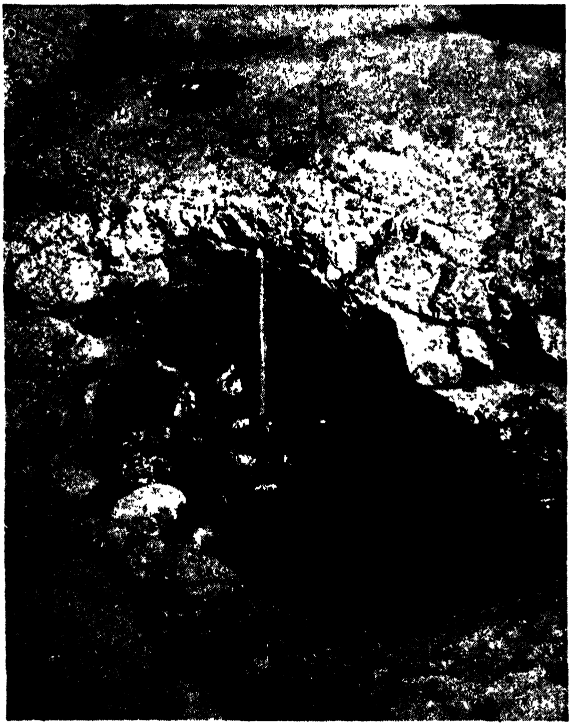

Fig. 35. Pothole in bed of Blackstone River, Massachusetts. *By W. C. Alden. Courtesy Geological Survey, U. S. Department of the Interior.*

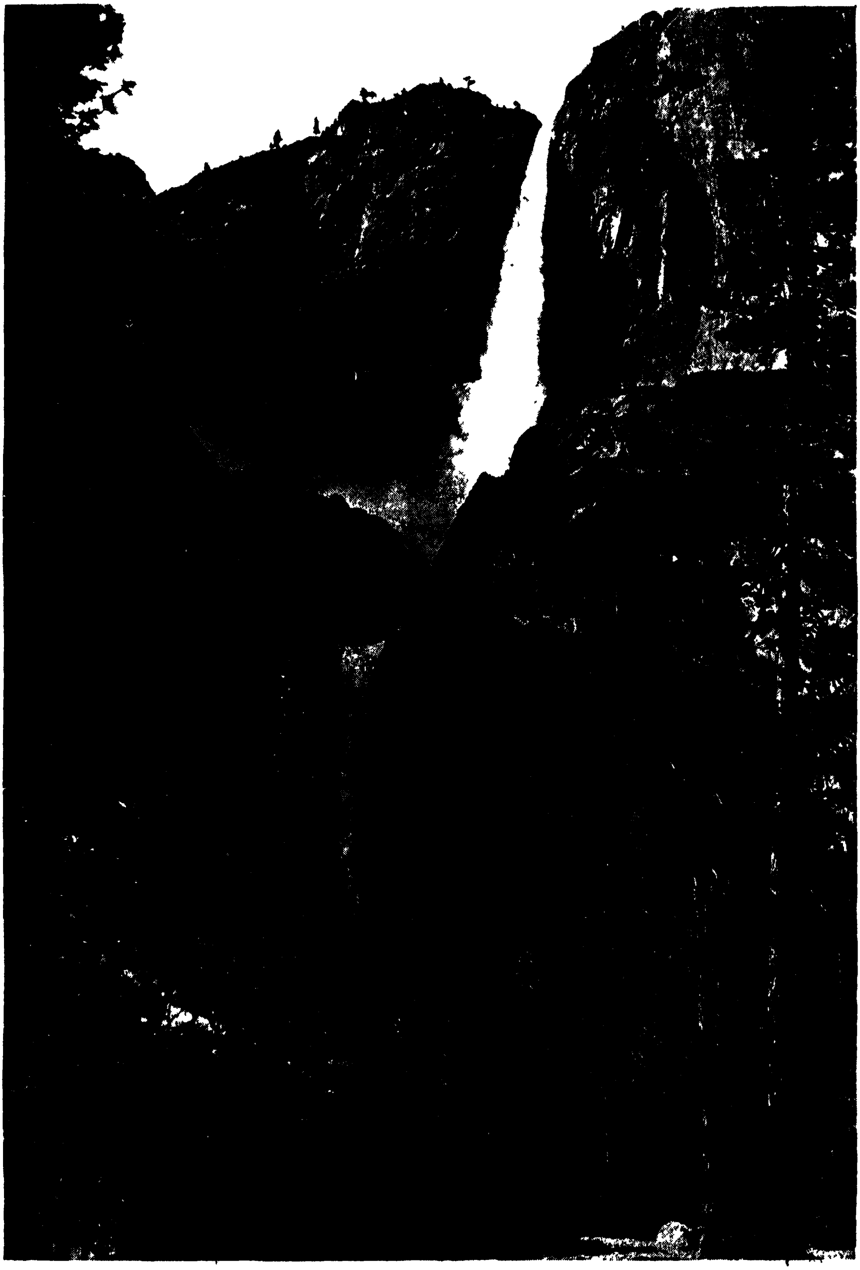

Fig. 36. Yosemite Falls, California. *By Ralph H. Anderson. Courtesy National Park Service, U. S. Department of the Interior.*

ering of the falls. A relatively hard rock stratum or an igneous dike standing in a vertical position makes waterfalls that will not recede, but will be gradually worn down. Of course, a river can not erode upstream from a falls below the lowest point on the lip of the falls, even though the rock upstream beyond the obstruction may be weak. A temporary base level is thus established, which continues in effect as long as the falls exist. Waterfalls are temporary features, even considering the life of a river. The forces of erosion eventually either cut through or into the resistant rock until its obstructive effect is destroyed.

Falls may be responsible for the cutting of *pot-holes* (Fig. 35), concave depressions in the bedrock surface at the foot of a waterfall. Potholes are worn by churning boulders agitated by the falling water.

Waterfalls create some of our most beautiful scenic features. The plunging torrents are also of great practical importance as a source of power. The United States contains a large number of waterfalls. Some in the mountainous states of the west drop from great heights (Fig. 36). The most famous falls in the country, however, are those of the Niagara River in New York and Ontario. Just before reaching the brink of these falls the river is divided by Goat Island into two channels, one of which lies in the United States. The American Falls is 1400 feet wide. Water passing over the Canadian or Horseshoe Falls drops into the lower gorge of Niagara River from a semicircular brink about 2600 feet in length. The vertical height of Niagara is about 165 feet. The magnificent Victoria Falls of the Zambezi River in Africa, first glimpsed by David Livingstone in 1855, far exceed Niagara in magnitude. The Zambezi river drops 420 feet from a basalt-capped plateau into a deep gorge. The channel at the brink is over a mile in width but is broken by a number of islands. The great height of Victoria Falls, combined with the enormous volume of water carried, makes it the greatest in the world. Seen by few people until a relatively short time ago, it has become much more accessible since the construction of the Cape to Cairo railroad, which bridges the canyon a short distance below the falls.

Piracy. The theft of water from one river by another is called *piracy*. In the headward growth of rivers, the larger often develop at the expense of the smaller. A large stream cuts its channel to a lower elevation than a small stream and, as it and its tributaries grow headward, they cut into the drainage areas of other streams and divert the water. Of course, the valley below the point of piracy is not

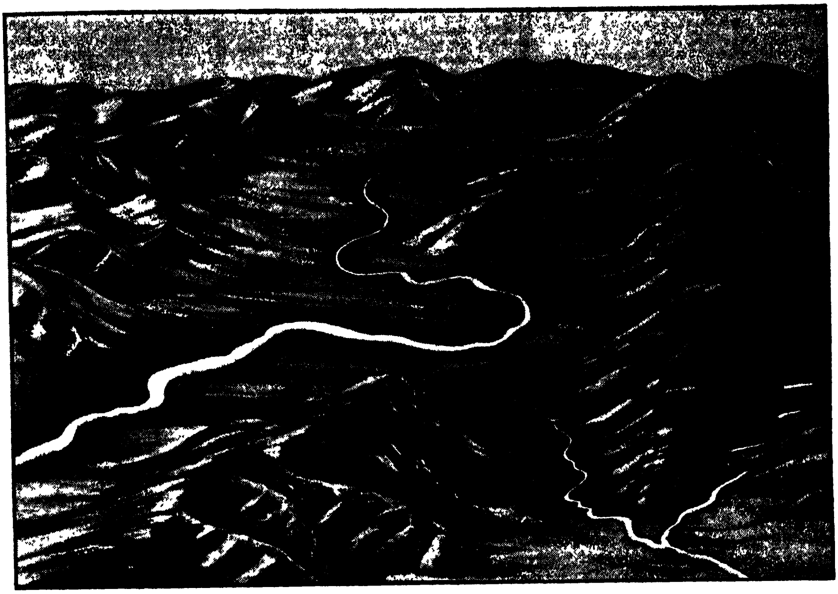

Fig. 37. A divide between two streams undergoing attack by tributary of stream on right. *By John Jesse Hayes.*

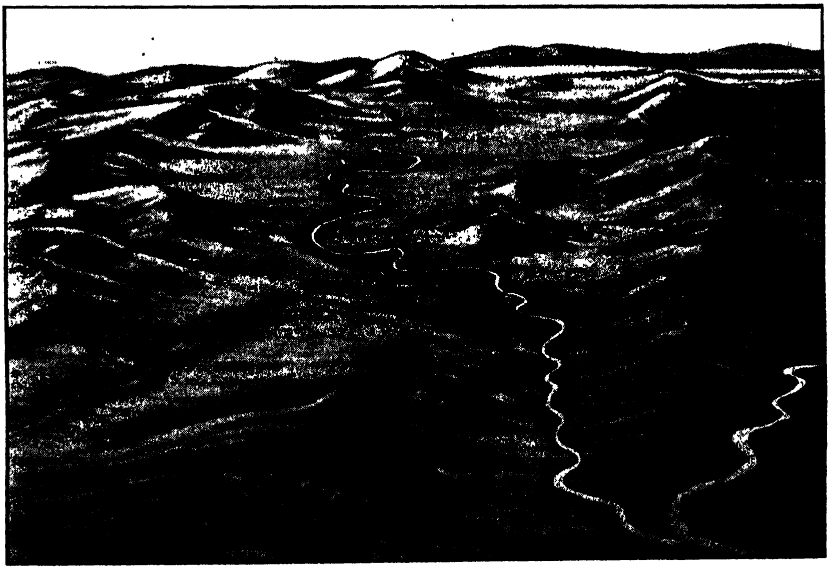

Fig. 38. The same region after the tributary has cut through the divide and captured the other stream. *By John Jesse Hayes.*

affected, but the stream occupying it is insignificant because the size of the area which it drains has been greatly diminished (Figs. 37 and 38). Piracy explains the condition noticeable in many localities, as in the Appalachian Mountain region, where a relatively small stream occupies a large valley. Many so-called notches or *wind gaps* in mountainous areas are valleys cut long ago by streams that were later diverted.

Land forms resulting from differential erosion. Differential erosion, the faster removal of less resistant rocks, allows more resistant rock masses to stand above the general level of the country. Weathering acts selectively, softening, decomposing, and disintegrating the less resistant rocks at a more rapid rate. Soluble rocks are dissolved and relatively insoluble rocks are left behind. The leaching agent may be surface water, but more work of this type is done by percolating and ground water. Wind, rain wash, and running water carry on differential erosion, removing the more easily eroded rock, and in many instances a distinctive topography results. Igneous rocks, in most instances, are more resistant than sedimentary rocks; hence they form hills, buttes, ridges and mountains in a region containing both types of rocks (Figs. 39 and 40). Stratified rocks of varying re-

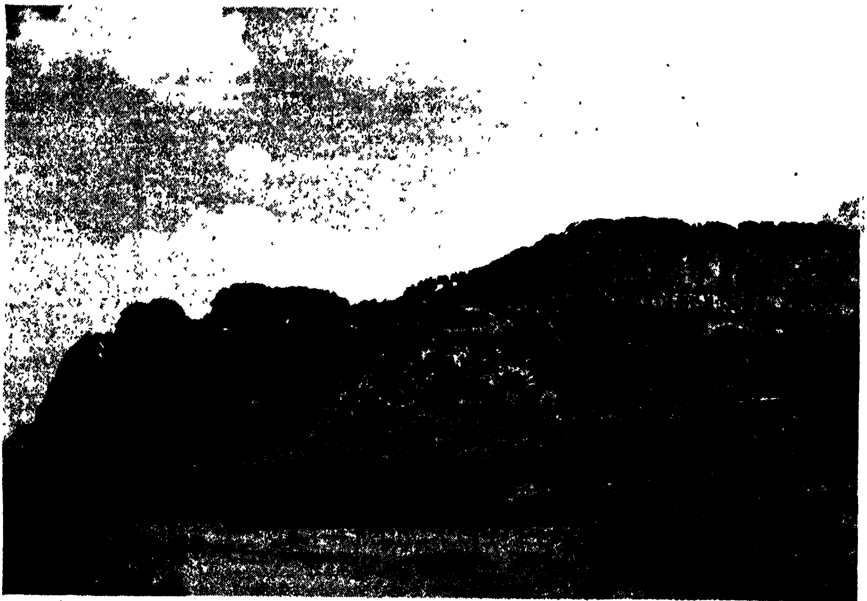

Fig. 39. Vertical igneous dikes make great rock walls where differential erosion has removed softer rock on either side. Spanish Peaks area, Colorado. *By M. V. Denny.*

sistance erode into distinct topographic forms, the shapes of which depend upon the structural position of the rock.

Mesas are flat-topped hills or mountains (Fig. 41). They are found only where the rocks are stratified (layered), and the strata, horizontal or nearly so, are of markedly unequal resistance to erosion. The "cap rock" of a mesa is invariably more resistant rock, such as sandstone, limestone, or lava. The underlying, weaker, soft rock exposed on the sides of the mesa is eroded by wind and running water. As the sides are cut back, the resistant cap rock falls off in large fragments, which roll to the bottom of the slope. When the mesa has shrunk in area so that but a small remnant of the original cap remains it is known as a *butte* (Figs. 42 and 43). This term is also popularly applied to other types of hills. When the cap rock is completely destroyed, the forces of erosion have free access to the less resistant underlying rock and the hill is soon destroyed.

Differential erosion of flat-lying sediments of unequal resistance

Fig. 40. Hard granitic rocks in background erode differentially to produce mountains. Near-vertical hogbacks of sandstone at right center. Front Range, including Pike's Peak, Colorado. *By H. L. Standley.*

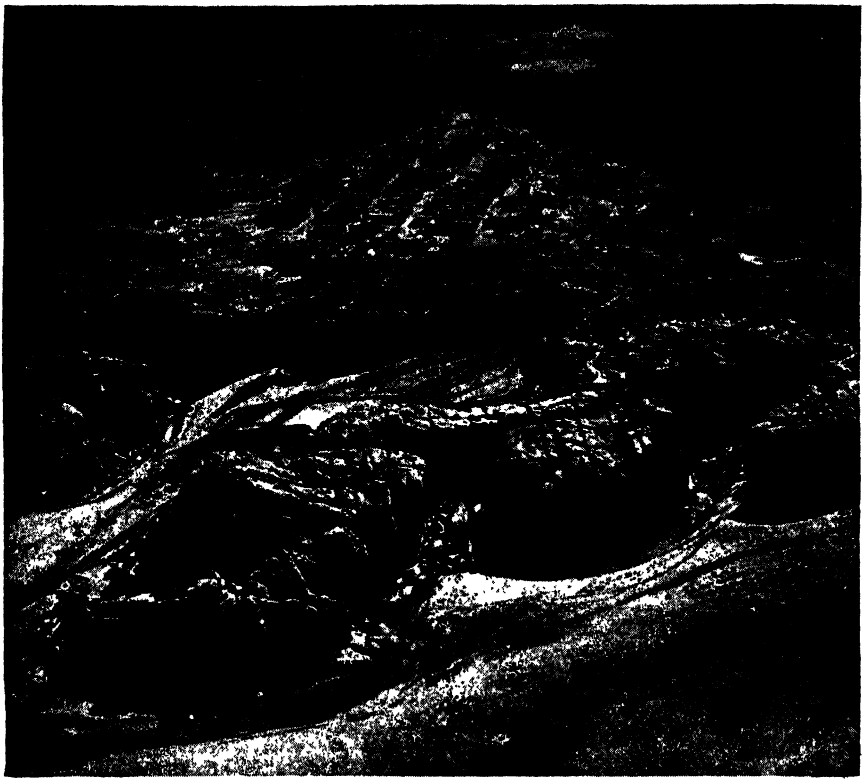

Fig. 41. Butte or small mesa used as village site by Indian tribe because of easy defense. Acoma, New Mexico. *By permission Spence Air Photos.*

outcropping on the sides of a valley creates *rock benches* (Fig. 44). A well known example is the Grand Canyon of the Colorado, where the walls consist of a series of steps from the rim down to the river eroded in alternating resistant sandstones and weak shales.

Differential erosion produces an entirely different type of topography where rocks of varying resistance are tilted. If the strata dip steeply, elongate ridges known as *hogbacks* are produced. The relatively hard "cap rock," which is tilted in conformity with the structure of the rocks, forms the surface of one flank (the *dip slope*) of the hogback (Fig. 40). As the underlying softer rock exposed on the other flank is eroded faster than the "cap rock," the latter is undercut and breaks off in fragments which roll to the foot of the slope. Continuation of this process, although it does not totally destroy the hogback, lowers its summit elevation, whereas the summit elevation of a mesa is not altered until the mesa itself is destroyed. Hogbacks commonly occur as a series of parallel ridges because of alternation of resistant and weak rocks (Fig. 45.) Such features are characteristic of areas underlain by folded sedimentary rocks, as are parts of the Appalachian Mountains of the eastern United States. Rivers occupy valleys between hogbacks. The tributaries on one side of each of these streams cut their valleys in the relatively soft rock underlying the "cap rock," whereas the tributaries on the other side of the stream flow down the dip slope of the rock capping the next hogback. The tributaries are relatively short and flow into the parent stream nearly at right angles. The typical stream pattern in a hogback region is called *trellis* because the main streams lie parallel to each other and the tributaries come in at, or nearly at, right angles.

Desert land forms. The arid lands of the southwestern part of the United States, from the Great Basin southward into Mexico, exhibit many erosion forms different from those occurring in more humid regions. Scattered mountain ranges with intermontane basins are the rule. Between the steep mountain fronts and the rela-

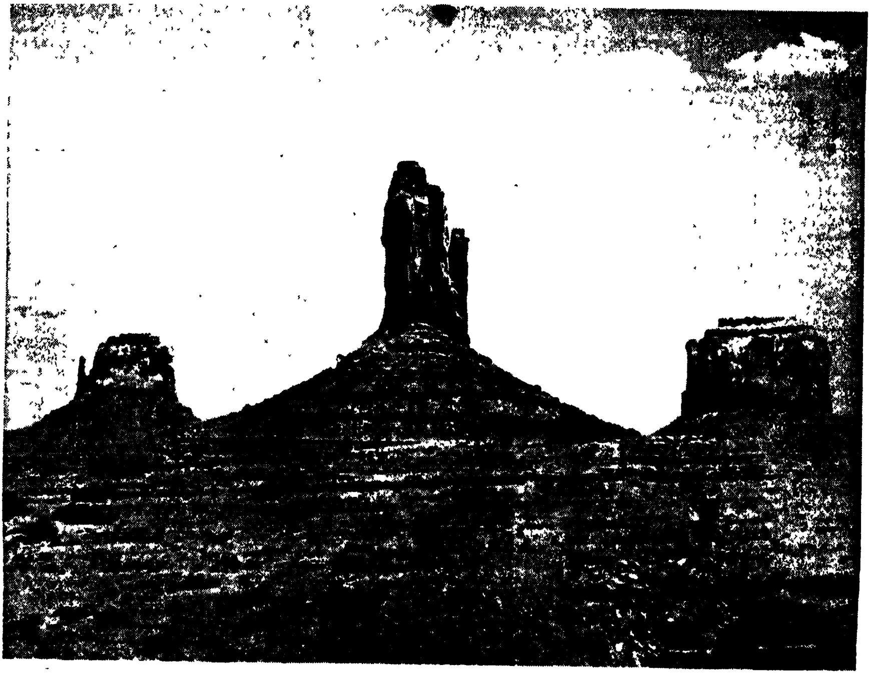

Fig. 42. Buttes in Monument Valley, Arizona. Thick sandstone bed capping shale and thin sandstone series. *By M. V. Denny.*

tively flat basin floors are great *pediments,* or apron-like rock slopes, which encircle the mountain ranges. The pediments may be thinly veneered with waste rock. The bed rock, regardless of kind or structure, is truncated and beveled so that it slopes away from the mountain core. It is believed that pediments are formed by a combination of weathering and the erosive activity of ephemeral streams draining the mountain ranges.

Another land form characteristic of arid (and semi-arid) regions is *badlands* (Fig. 46). In addition to lack of protective vegetation, easily eroded bedrock is essential to badland formation.

Degradation. The ultimate objective of running water and other forces of erosion is to level off the continents until they stand at a minimum elevation above the sea. The depth to which rivers can erode is definitely limited; a river entering the ocean can cut its channel no deeper than a few feet below sea level, and the downward erosion of a river entering a lake is limited by the approximate level of that lake. The lower limit of downward erosion of a continent is called *base level.* It has been shown that with erosion of the lands, sea level would rise because of deposition of

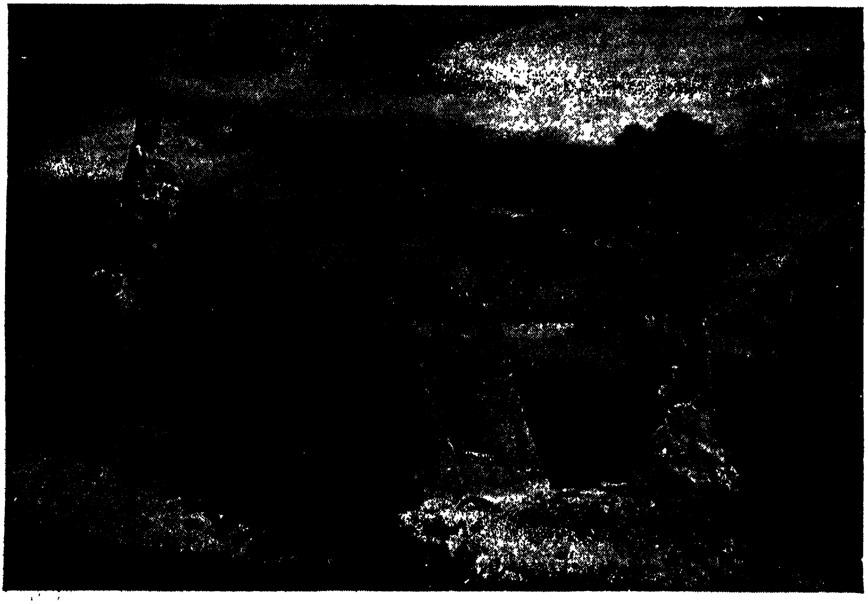

Fig. 43. Toadstool rocks, or buttes in miniature. Cap rock is indurated (hardened) sandstone. Monument Park, near Colorado Springs, Colorado.
By M. V. Denny.

sediment in the oceans, and therefore ultimate base level is higher than base level established by present sea level. A lake establishes a *temporary base level* for entering streams, temporary because eventually the outlet stream will cut its channel to sufficient depth to

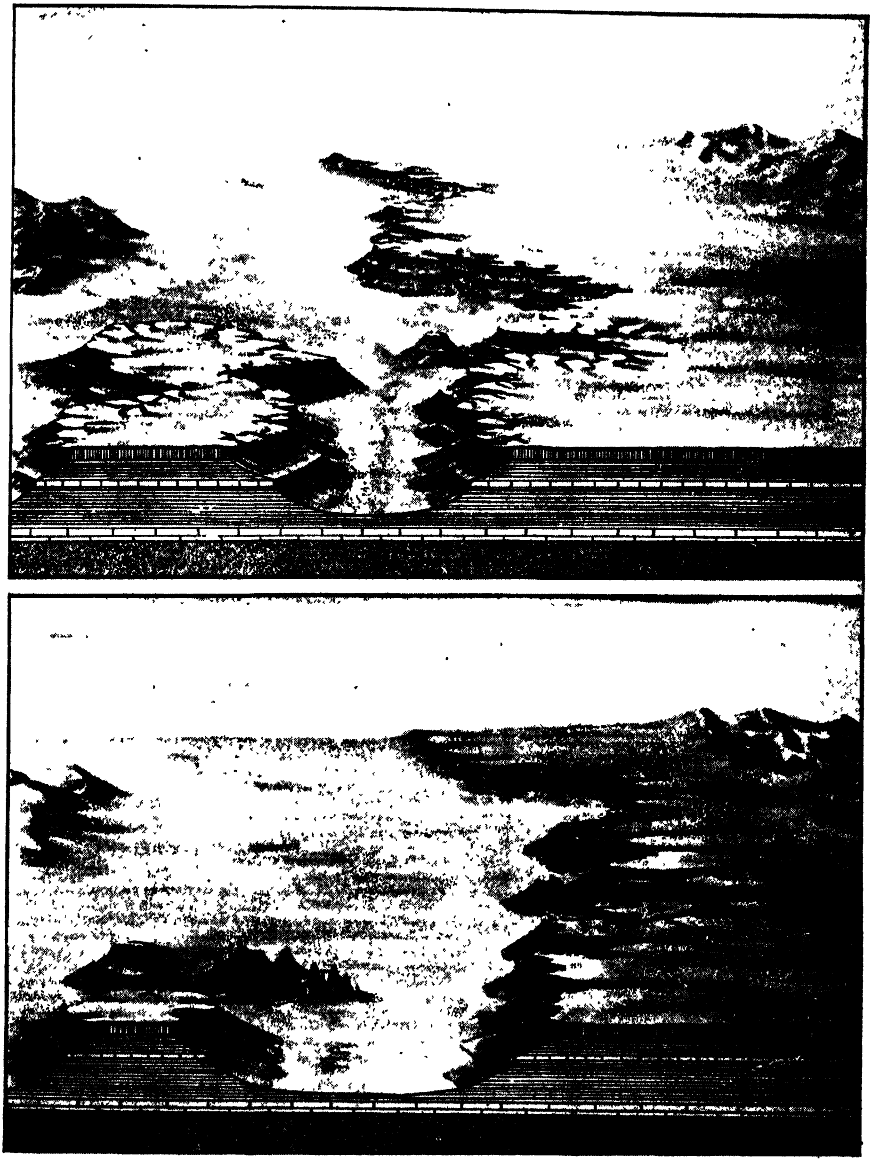

Fig. 44. Dissection of a plateau surfaced with a layer of relatively resistant flat-lying "cap rock." The origin of mesas and buttes. *By John Jesse Hayes.*

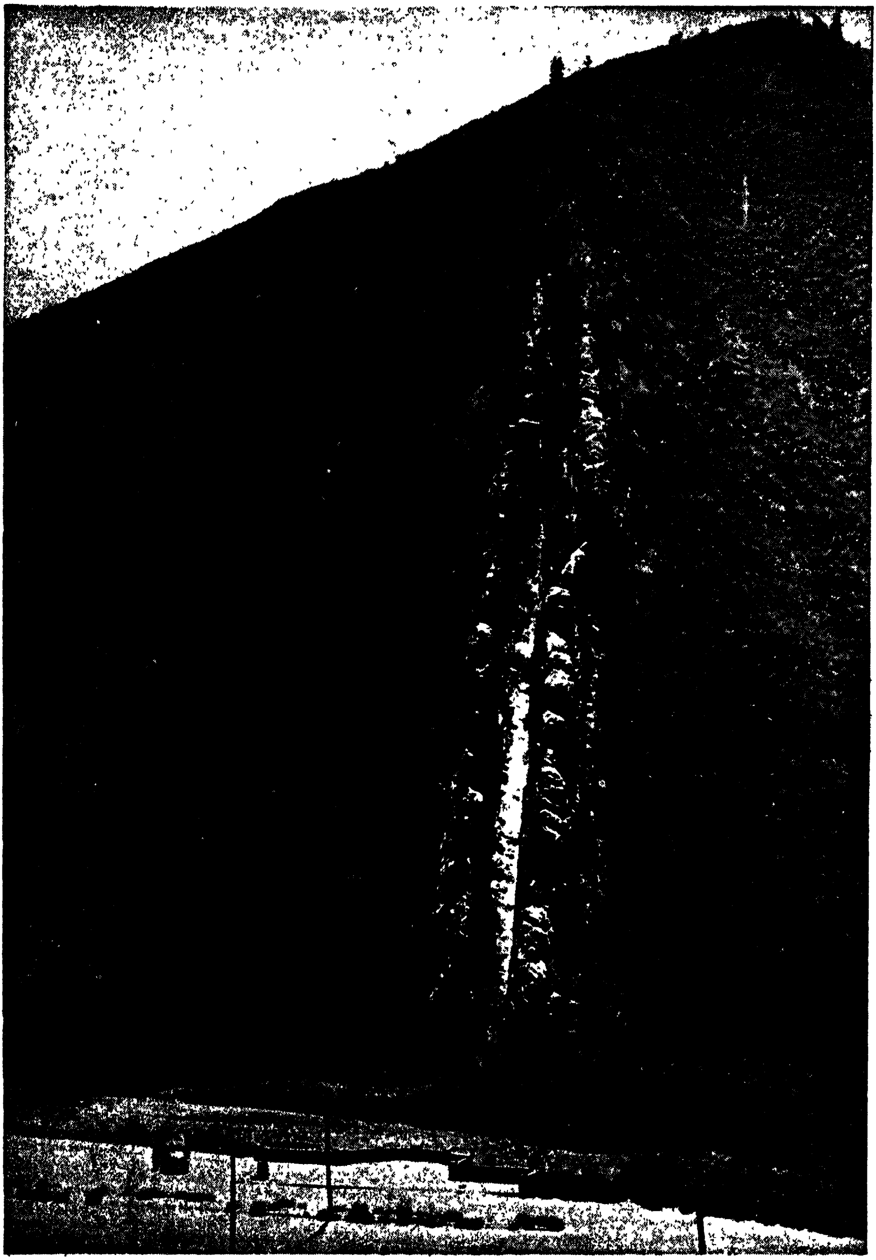

Fig. 45. Hogbacks in miniature. Vertical strata, with two resistant beds standing in bas relief and a softer bed between making the "Devil's Slide," Weber Canyon, Utah. *By M. V. Denny.*

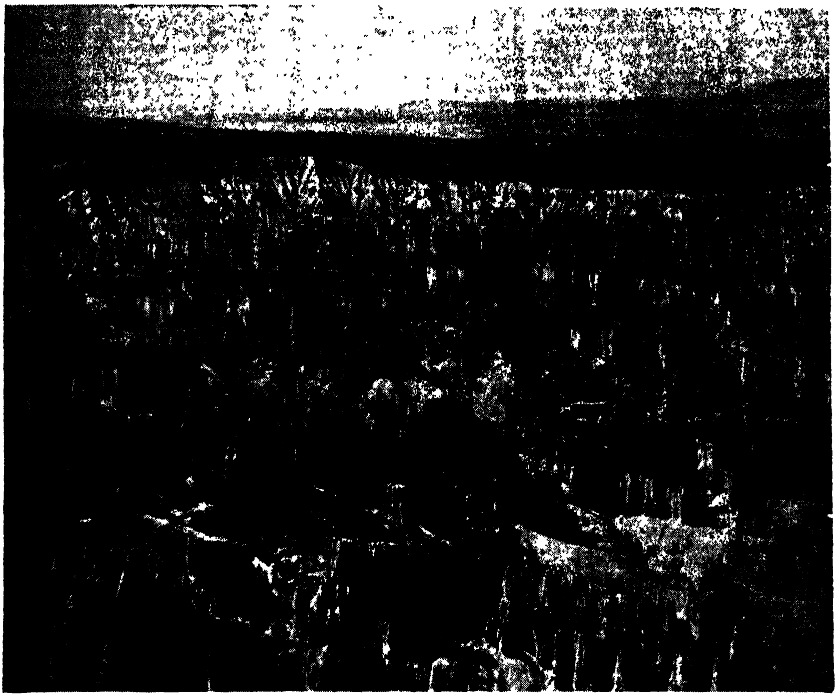

Fig. 46. Bryce Canyon National Park, Utah, from Inspiration Point. An extreme example of badlands. *Courtesy Union Pacific Railroad.*

drain the lake. A hard ledge of rock in a river channel may establish a temporary base level upstream.

No continents have been worn down to base level during the present cycle of erosion. In recent time, parts of all of the continents have been elevated high above the sea, so that, so far as geological time is concerned, degradation in the present erosion cycle in most places has been going on for but a short while. In the more distant geologic past, erosion reduced large areas of the continents many times. In fact, the mountains and high plateaus of the present are not typical of the past, for over the greater part of traceable geological time the continents stood at relatively low elevation.

A region that has been reduced to generally low elevation and subdued topography by erosion is called a *peneplain.* Literally this word means "almost a plain," but actually no peneplain is ever very flat, for outcropping masses of more resistant rocks form local hills and ridges. Prominent hills that rise above the general surface of a peneplain are known as *monadnocks.*

That part of North America contiguous to Hudson Bay is a peneplain, modified by glaciation. Much smaller peneplained areas exist in a few other parts of the continent. Elsewhere, running water and the other agents of erosion still have a great task before them, and the higher the elevation the greater is the volume of material yet to be removed before complete gradation is accomplished. The average height of the North American continent is about 2,000 feet. The agents of erosion lower the surface of the continent at an estimated rate of one foot every five to ten thousand years. It is not feasible, however, to estimate the number of years it would take at that rate to reduce the continent to base level because, in the future, the rate will become increasingly less due to decreased stream gradients. Climatic changes, especially in rainfall, will alter the degradation rate. Furthermore, interruptions brought about by *diastrophism* (movements of the earth's crust) undoubtedly will take place. The uplift of a continent or a part of a continent increases the volume of material to be eroded before base level can be reached. On the other hand, depression of the continent would bring the ultimate goal that much nearer. We know from studies in physiography and historical geology that many such interruptions have taken place, both in the recent and in the geological past.

RESULTS OF DEPOSITION BY RUNNING WATER

Stratification of sediment. Running water is a very effective sorting agent. The sediment deposited at any one point in the bed of a stream will be alike in size because it is all adjusted to the same current velocity. Gravel, sand, and silt therefore occur in separate and distinct deposits.

Variations in stream velocity at any point at different times result in the deposition of sediment in layers of different texture. One layer may be composed of gravel, and the next of sand. Then an increase in velocity may cause deposition of another layer of gravel. In this way, stratification, a characteristic of all sediment deposited by agents capable of sorting, is produced.

Alluvial fans. Where streams change velocity suddenly upon emerging from an upland area onto a plain, an *alluvial fan* is built (Figs. 47, 48, and 49). The silt, sand, gravel, and boulders carried by the faster moving water are dropped in a fan-shaped deposit, with the apex of the fan at or in the canyon mouth and the rest of the fan spreading over the adjacent lowlands. The fan shape re-

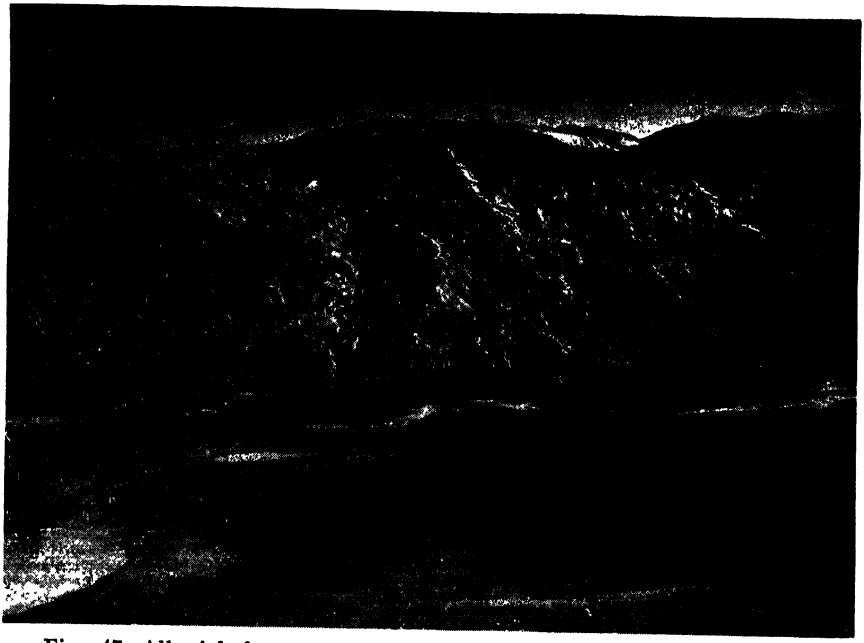

Fig. 47. Alluvial fans, Death Valley, California. *By permission Spence Air Photos.*

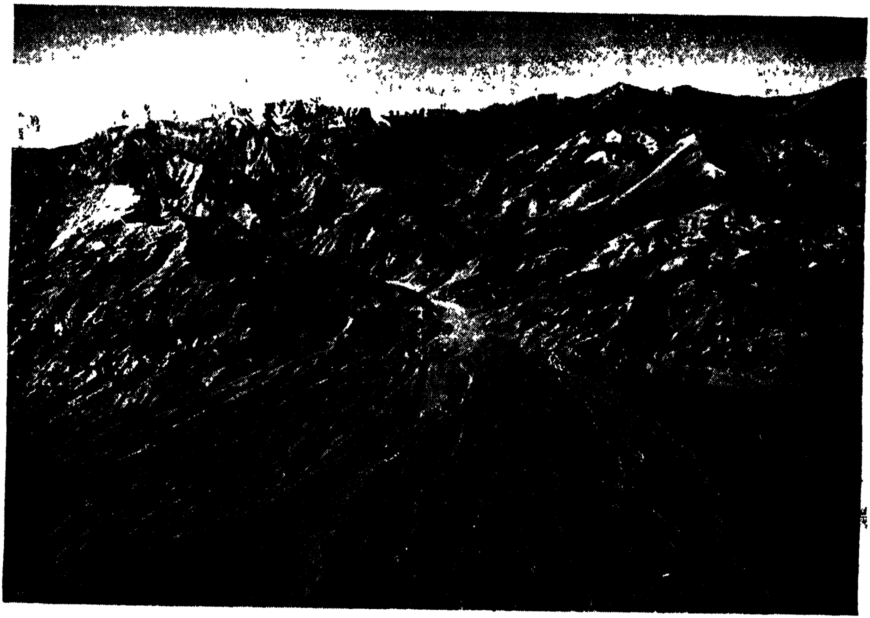

Fig. 48. Apex of alluvial fan. Death Valley, California. *By permission Spence Air Photos.*

sults from the choking of the stream with sediment at the mouth of the canyon, because of the sudden lessening of gradient at that point. The stream is thus diverted into another position where it once more becomes filled with sediment and so must move again. By deploying back and forth from a fixed point (the canyon mouth) the stream builds a low cone which extends in a half circle from the mountain front on one side of the canyon mouth around to the mountain front on the other side. As erosion proceeds, deposition may also extend the apex of the fan up the canyon.

Flood-plains. The flats at the bottom of valleys are called *flood-plains.* The establishment of a flood-plain is brought about by inequalities or obstructions in the stream bed, which divert the current from a straight course. Centrifugal force creates the highest current velocities on the outside of the curves in the stream; minimum velocities occur on the inside, or concave side, of the curves. Therefore, lateral erosion, or *planation,* is active where the stream swings against the bank, and the material eroded from this point will be carried downstream to be deposited on the inside of other curves where the velocity is low. In its early stages, a river flood-plain is discontinuous and is located first on one side of the stream and then on

Fig. 49. Compound alluvial fans which have begun to bury low hills in center. Death Valley, California. ***By permission Spence Air Photos.***

the other in the concavities of the river bends. But, as the valley bottom is widened by lateral planation, the curves shift downstream, so that at one time or another all parts of the valley bottom receive sediment. In this way a flood-plain is built. During floods, parts of this low-lying river-made land are inundated (hence the name "flood-plain"), and a layer of silt or other sediment is left behind when the waters recede.

Many cities and smaller communities are built upon flood-plains because of their flatness and, in earlier days at least, because of the use made of rivers for communication and transportation. The soils of most flood-plains are fertile and are intensively farmed.

Meanders. The winding of a stream on its flood-plain is known as *meandering.* It is a continuation of the same process of erosion on the outside of curves and deposition on the inside that initiated construction of the flood-plain. When lateral planation has widened the valley floor sufficiently, the curving path of the river is largely confined to the flood-plain which it built. During construction of the flood-plain, the sediment is reworked many times through erosion and redeposition. The relative ease of erosion of flood-plain material accelerates the development of meanders. The centrifugal force of the current on the outside of a curve causes it to "eat" into the bank, thus increasing the curvature of the stream at that point. At the same time the adjacent but opposite curves also are increasing their curvature by lateral erosion. Consequently, the course of a river on a flood plain becomes a series of loops which, in general, lie across the trend of the valley. Because of these meanders, river traffic may have to go ten or fifteen miles to cover a distance of but three or four miles up or down the valley.

Eventually, the loops enlarge to such an extent that the distance across a "neck" becomes very short. A stream, cutting into its banks, may break through a meander, especially during floods, thereby shortening itself and abandoning several miles of river bed. In many instances this process is hastened during a flood when the river, covering most or all of the flood plain, scours out the short cut. Abandoned meanders are known as *oxbows,* many of which contain lakes. Hundreds of oxbows and oxbow lakes are present along the lower Mississippi River.

Mark Twain in *Life on the Mississippi* writes with his characteristic humor of his experiences, and of the vagaries of the Mississippi River, as follows:

> The water cuts the alluvial banks of the "lower" river into deep horseshoe curves; so deep, indeed, that in some places if you were to get ashore at one extremity of the horseshoe and walk across the neck, half or three-quarters of a mile, you could sit down and rest a couple of hours while your steamer was coming around the long elbow at a speed of ten miles an hour to take you on board again. . . . Once there was a neck opposite Port Hudson, Louisiana, which was only half a mile across in its narrowest place. You could walk across there in fifteen minutes; but if you made the journey around the cape on a raft, you traveled thirty-five miles to accomplish the same thing. In 1722 the river darted through that neck, deserted its old bed, and thus shortened itself thirty-five miles.

Twain then lists a number of other occurrences of river shortening, some prehistoric but many since his own day on the Mississippi, and draws the following conclusion:

> In the space of 176 years the lower Mississippi has shortened itself 242 miles. That is an average of a trifle over one mile and a third per year. Therefore, any calm person, who is not blind or idiotic, can see that . . . just a million years ago next November the Lower Mississippi River was upward of 1,300,000 miles long, and stuck out over the Gulf of Mexico like a fishing-rod, and by the same token any person can see that 742 years from now the Lower Mississippi will be only a mile and three-quarters long, and Cairo and New Orleans will have joined their streets together, and be plodding comfortably along under a single mayor and a mutual board of aldermen. There is something fascinating about science. One gets such wholesome returns of conjecture out of such a trifling investment of fact.[1]

Levees. Water overflowing the banks of a river suffers a decrease in velocity due to the relatively greater friction of the thinner sheet of water against the surface over which it flows. This brings about deposition, and eventually a natural *levee* will be built on both sides of the river parallel to the banks. Along parts of the lower Mississippi the highest land for miles around is the river banks.

Deltas. Deltas are built where a river enters a lake or the sea. The sudden diminution of velocity causes deposition of sediment. As the channel becomes choked, the river seeks another channel, or divides into a number of branches, each one of which enters the lake or sea at a different point. Dendritic branching, somewhat similar to the forking of the tributaries upstream, takes place on the delta, but it is on a smaller scale and is directed downstream instead of upstream.

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[1] Stormfield Edition, Vol. 12, pp. 153-156. New York: Harper & Brothers, 1929.

Some of the major rivers have extended themselves several hundred miles out into the ocean through delta building. The city of New Orleans is built upon the delta of the Mississippi about 115 miles above the present mouth of the river. Much of the fertile land of Egypt lies upon the delta of the Nile, and most of the coastal towns of Alaska are built upon deltas, the only flat or nearly flat land available.

Placer deposits. Placer deposits contain valuable minerals which have been mechanically transported and then deposited in abundance because they possess specific gravities greater than that of the associated minerals (see Fig. 10). Three conditions are essential to the formation of placer deposits. In the first place, the region supplying the minerals to the placers must be one where erosion proceeds very rapidly, for no mineral is completely insoluble or chemically inert, and if denudation is slow the minerals will be destroyed. Second, the mineral itself must be resistant to solution and decay, otherwise it will not survive even though erosion be rapid. Lastly, the mineral must be heavier than the valueless material that is transported at the same time, or it will not be sorted and deposited in concentrated masses.

Most placer deposits occur in the beds of streams. The placer minerals are a part of the stream alluvium and consequently are in the process of being shifted down the valley, unless the stream has reached base level. Flood waters roll the boulders and gravel downstream, and the relatively heavy placer minerals work through the crevices developed during this shuffling and eventually find lodgement on top of the bed rock beneath the alluvium. Knowing this, the placer miner loses no time in getting down to the deepest zone of gravel, for there the greatest values occur.

The prospector knows that placer deposits are not always confined to the present streams but are found in ancient abandoned water courses. The latecomers in the Klondike rush of 1898 found the beds of Klondike and neighboring creeks completely staked. They discovered, however, that high on the flanks of Klondike valley were remnants of an old stream channel and that its gravels likewise contained placer gold.

Gold is the best known of placer minerals. Placer gold is almost invariably discovered before the bed-rock deposits are found. Its presence can readily be detected by testing river alluvium in a miner's pan. Following the discovery of placer gold comes the finding of the "mother lode" from which the placer deposits have been derived. In many instances this mother lode is sufficiently rich to exploit, and the mining of vein gold may continue for many decades after the alluvial deposits have been exhausted. However, in some localities it has been found that the gold or other placer mineral is not sufficiently concentrated in the source rock for profitable mining but that the alluvial deposits can be worked successfully because of the greater concentration brought about through the action of running water and the lesser cost of placer mining.

Most of the world's platinum once came from placer deposits. Dark-colored igneous rocks in the Ural Mountains of the U.S.S.R. contain scattered grains of platinum and allied metals, but in too lean a concentration to be minable ore bodies. However, the alluvium in the stream valleys draining the area contains sufficient platinum to be workable. Other important placer minerals are the ores of tin and tungsten. In addition, several non-metallic minerals, including diamonds and rubies, occur in placer deposits.

Sand and gravel deposits. Sand and gravel, products of the wearing away of rocks exposed at the earth's surface, consist of the more resistant minerals present in those rocks. The average sand is over 90 per cent quartz, because of the initial abundance of this mineral and its resistance to processes of decay. Sand and gravel are transported, mainly by running water, from their point of origin to a place of deposition. During this transportation the rock particles become worn and rounded.

Commercial deposits of sand and gravel are scattered over the continents in a variety of environments. Many stream beds contain sand, or a mixture of sand and gravel, that can be excavated or dredged. Unlike most other mineral deposits, the sand and gravel in a river bed may be periodically replenished, since every flood brings in a fresh supply. The usual river flood plain also, although composed mostly of silt, has within it zones of coarser material, marking former channels of the river, which are valuable sources of sand and gravel, and also of ground water. Sand and gravel are obtained in some regions from terrace deposits, remnants of older and higher flood plains. Such deposits ordinarily are discontinuous, because of erosion by streams belonging to the present drainage system; but, once the trend of the old river which formed the deposits has been determined by the locations of two or three remnants, it may be possible to prospect in the directions indicated and discover additional supplies.

The principal use of sand and gravel is for building and highway construction, in preparation of concrete, mortar, asphalt, and road surfacing. Sand is important also in the manufacture of glass and of molds in which metal forms are cast, for abrasive purposes (sand blasting), as a refractory used in lining furnaces, and as engine sand which the locomotive engineer pours onto the rails to keep the wheels from slipping.

CLASSIFICATION OF STREAMS

Streams may be classified in a variety of ways. One classification is based upon the stages of development of a stream and its valley. This is a classification measured not in years but in the progress of the stream through its life history. Another classification is based upon origin; still others are concerned with the relationship between the stream and the attitude of the underlying rocks and with changes which have taken place that interrupted the normal history of the stream. These classifications are discussed below.

Stages of stream and valley development. The physiographer, or student of the various forms of topography, designates streams and their valleys as either *young, mature,* or *old.* These age terms are purely relative and are not definable in years. A youthful stream and its valley may be older in years than another which has reached maturity, or even old age.

The use of these terms needs explanation. For example, an individual standing on the rim of Grand Canyon considers this valley very old, for without doubt the Colorado River has taken many hundreds of thousands of years to cut the gorge. However, the physiographer calls the canyon young, because it is relatively narrow and the river at its bottom is still cutting downward at a fairly rapid rate.

The age terms are not ordinarily applicable to a stream and valley along their entire length. Many streams and valleys are old near the mouth, young near the headwaters, and mature in between. The age can be determined in most instances either by direct study of the stream and valley or by study of maps or airplane photographs of them.

Streams and valleys are *youthful* from the time the stream starts eroding its valley until the *profile of equilibrium* has been established. A stream approaching grade reaches the profile of equilibrium when the work it has to do approximately balances its capacity to do work. In early youth, many lakes may occur along the course of a stream. These are eliminated by filling with sediment and by down-

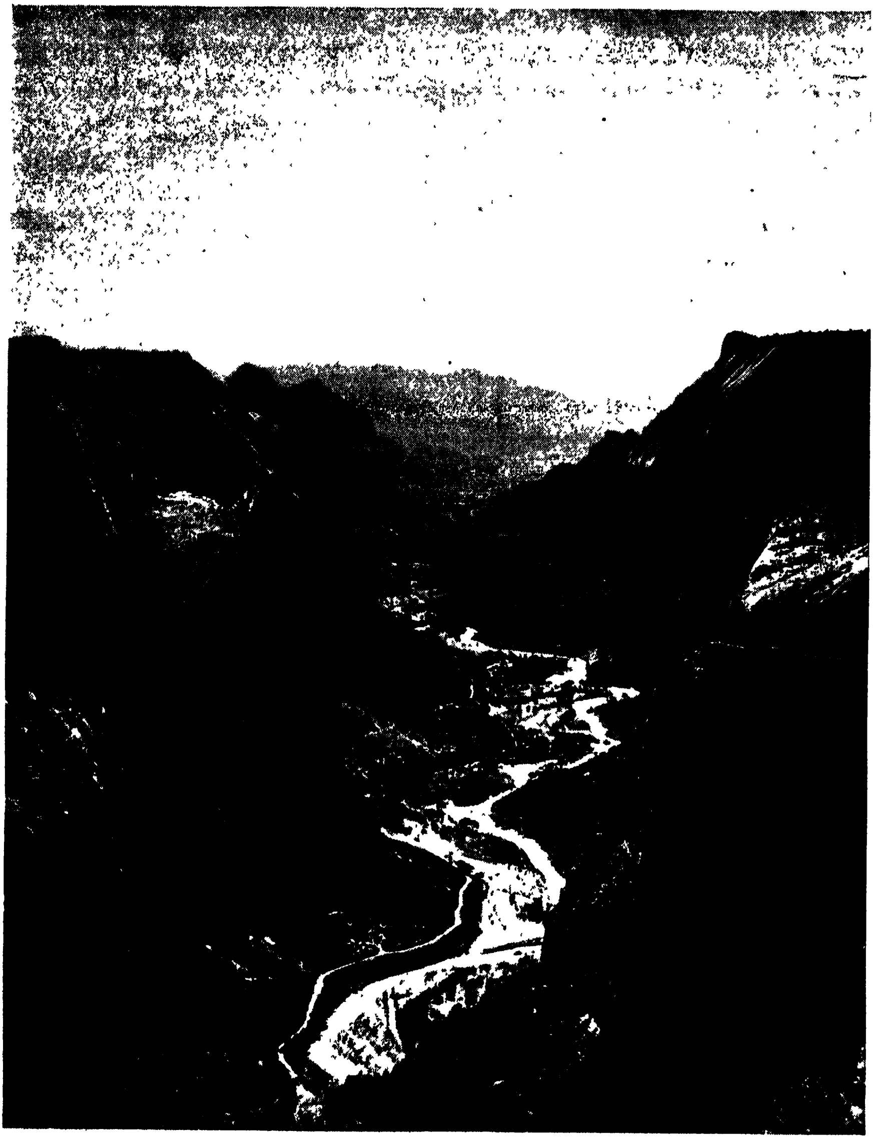

Fig. 50. Young V-shaped valley cut into cliff-forming sandstone. Talus cones cover most of narrow valley floor. Zion Canyon from Observation Point. *Photo by Grant. Courtesy U. S. Department of the Interior.*

cutting at the outlet. There follows a period when rapids, cascades, and even waterfalls occur along the route from headwaters to mouth. Obviously the gradient of the stream is greatest during this stage. Erosion is dominant during youth, with the stream cutting steep-walled, V-shaped valleys as shown in Fig. 50. Valley cutting is vigorous both laterally and vertically. The Colorado River in the Grand Canyon at Bright Angel Trail has cut a gorge about a mile deep, but at the same time the valley has been widened at the top by other erosional processes for a distance of about fourteen miles.

With the establishment of the profile of equilibrium, streams and their valleys become *mature.* Downcutting is exceedingly slow, and lateral erosion increases relatively, but not actually, in effectiveness. Narrow erosion plains are excavated along one or both sides of the stream and are covered with sediment during times of flood. Thus is initiated the river flood plain which widens as the river grows older.

With the establishment of a valley flat, the stream is free to meander at will. Coincident with the building of the flood plain, the sides of a mature valley develop increasingly gentle slopes, except locally where meander loops extend to the flood plain edge and undercut the rock on the sides of the valley. In some instances an over-supply of sediment, especially during low water, causes the stream to flow through a net-work or *"braid"* of channels because the stream bed is choked with bars of gravel, sand, or silt.

Full maturity is reached when the width of the meander belt equals the width of the valley floor. The meander belt is the territory lying between imaginary lines connecting the outermost loops on each side of the stream. Eventually, when the lateral planation process has widened the valley floor so that it is several times the width of the meander belt, the stream and valley are *old.* While this is not as distinct a demarcation as that between youth and maturity, fully developed old age is easy to recognize. Old river valleys have extremely wide flood plains and are bordered by such low divides that the slope of their sides may be almost imperceptible. Oxbows and oxbow lakes are common on flood plains of old streams because of frequent cutting off of meanders (Fig. 51).

Stages in the dissection of a land mass. Physiographers also use the terms "young," "mature," and "old" in reference to the stage of dissection of a land mass. The ages of the valleys and streams incised in a land mass do not necessarily coincide with the stage of dissection of that land mass. The basis for age classification of a land mass is the amount of work accomplished. A plateau which is cut into by only a few streams still contains most of the rock which it is the task of the agents of erosion to remove. Therefore, such a plateau is youthful (Fig. 52). It is drained by a relatively small number of widely spaced streams, separated by divides which are nearly flat. A land mass becomes mature when stream erosion has destroyed the broad plateau surfaces but has not yet lowered the divides very far below their original elevation. In regions high above sea level, mature topography is a succession of mountainous ridges separated by deep canyons; in a land mass which was initially at lower elevation, the mature landscape is a complex of lower, rounded or sharp-crested hills and broader valleys. In any case, maturity is characterized by the maximum diversity of relief which will be developed in a region during the existing cycle.

By the time old age has been reached, the greater part of the rock originally above sea level has been removed; the divides are low with gentle slopes extending down to the valley flats. The ultimate in the dissection of a land mass is the peneplain, a nearly even surface of almost indistinguishable divides and broad flats. The peneplain stage is the last one in the cycle of erosion (p. 122); an uplift of the peneplain will start a new cycle.

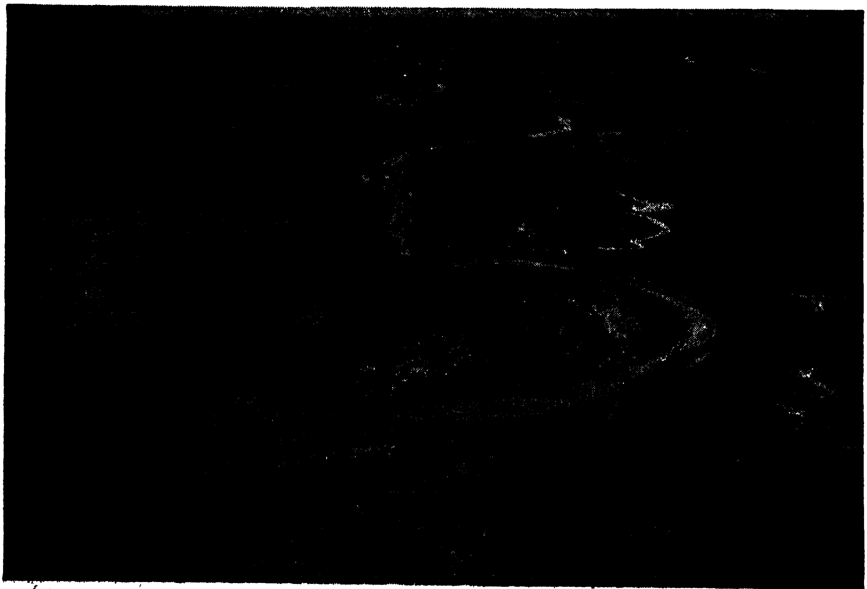

Fig. 51. Stream in old age, with wide flood plain and oxbow lakes. Pecos River at Roswell, New Mexico. ***By permission Spence Air Photos.***

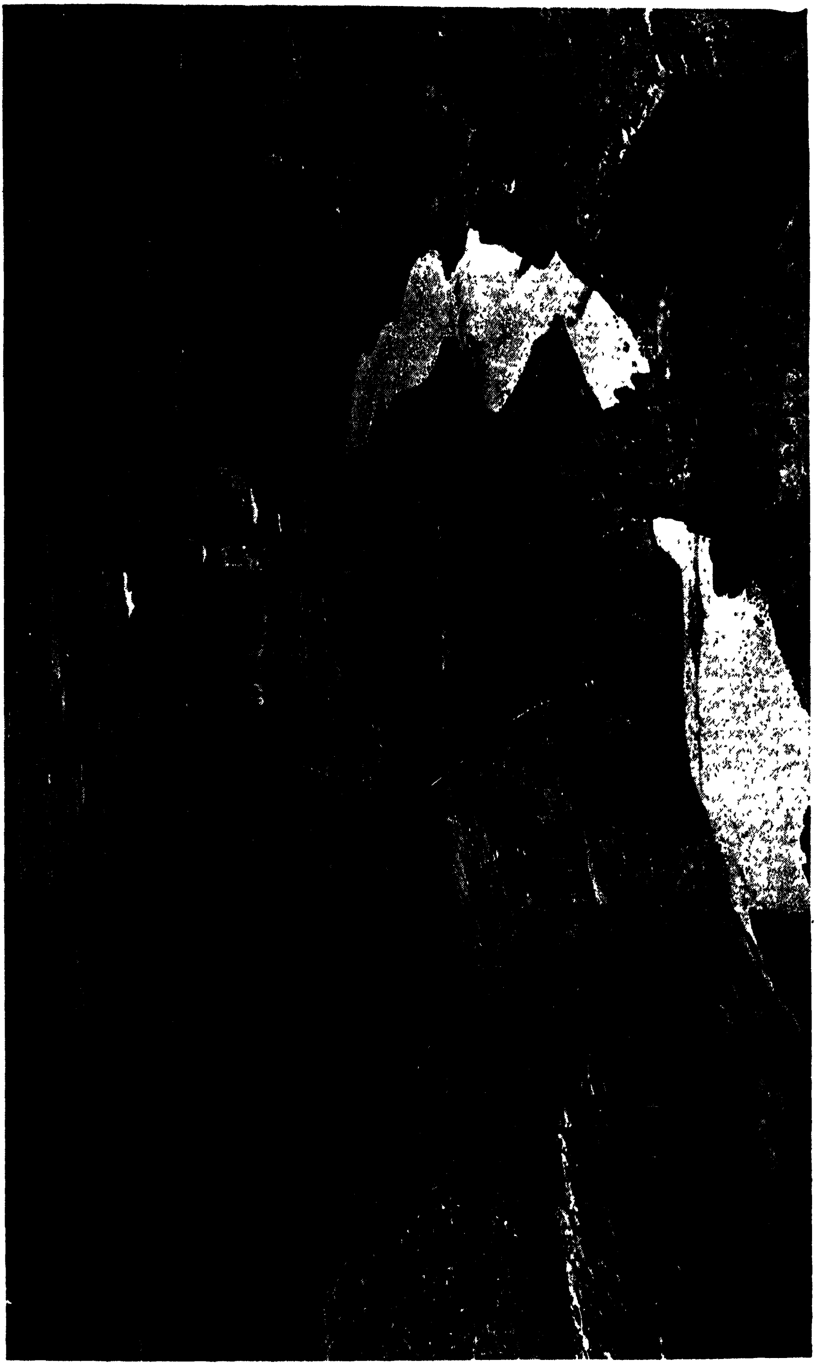

Fig. 52. Youthful topography. Flat plateau surface incised by single stream with few tributaries. Canyon de Chelly, Arizona.

By permission Spence Air Photos.

Classification of streams according to origin. The question as to why a stream flows in a given direction goes back to conditions existing when the stream first began cutting its valley. Most stream courses are determined by the initial slope of the land which favored a certain direction of flow. Such streams are called *consequent* streams because they are evolved upon the initial topography and have their courses determined by depressions in its slopes. If the course of the consequent (or any other) stream carries it across belts of more easily eroded rock, naturally the tributaries, which develop by headward erosion, will tend to follow the outcrop of the weaker rocks. Such streams, because they are dependent for their position upon the presence of rocks of lesser resistance to erosion, are called *subsequent.* The belts of weak rock may be outcropping beds of shale or other easily eroded sedimentary rock. They may even be igneous or metamorphic rocks which are more readily eroded than the surrounding rock. The tributaries of subsequent streams, where the latter are incised into tilted layers of weaker rocks, tend to develop headward directly up the dip slopes and scarp faces of the

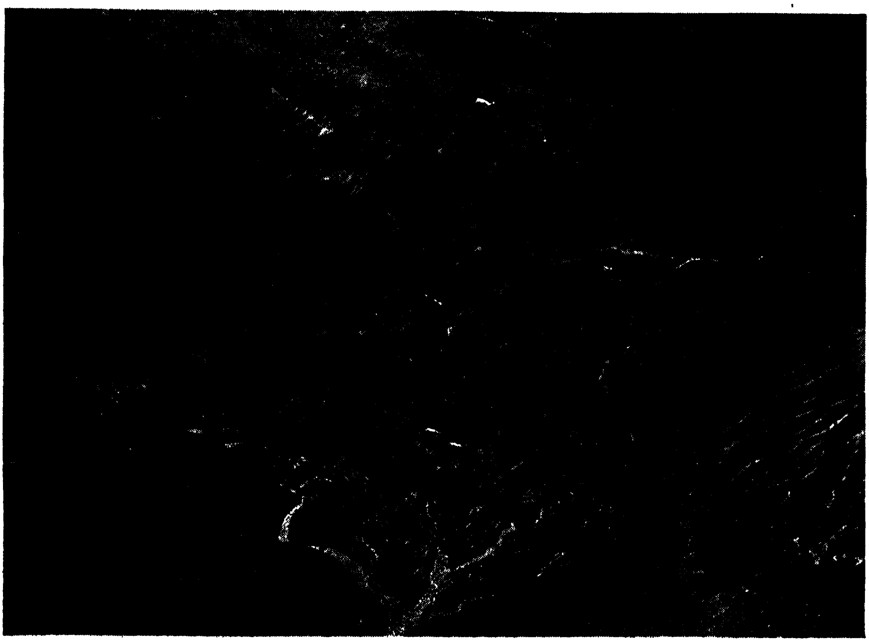

Fig. 53. Rivers which run across the "grain" of the rocks. These streams cut through the hard rock ridges; they are either antecedent or superposed. Arawatz Mountains, San Bernardino County, California. ***By permission Spence Air Photos.***

adjacent harder layers. The right angle branching produces a trellis drainage pattern instead of the more usual *dendritic* pattern. In some cases a subsequent stream does not follow a zone of weak rock, but a zone along which all rocks have been so weakened by earth movements as to be easily attacked by running water.

Classification of streams according to relationship with underlying rock structure. Some streams, regardless of origin, fail to conform with the structure of the rocks in which they are entrenched. In other words, a stream may flow across both weak and resistant formations (Fig. 53), across upfolds and downfolds, and even across blocks of the earth's crust which have been elevated along faults above the surrounding areas. This lack of conformity can be explained in two ways. If the movements of the earth's crust took place very slowly, the river may have been able to maintain its course by cutting through the upward moving area as fast as movement occurred. In this case we conclude that the stream acquired its course before deformation started. It is therefore referred to as *antecedent.*

The other explanation is that the rock structures to which the stream fails to conform already existed, but were blanketed by overlying rocks which did not possess these structures. The stream was developed on the higher surface in harmony with conditions existing there. When it eroded into the different structures below, the streams did not conform to their new surroundings. This type of stream is *superposed* (superimposed) because it has been imposed from above, where conditions were quite dissimilar.

Classification of streams according to effects produced by changes in level. The earth's crust is by no means stable. Actually some sections are slowly being elevated and others are slowly being depressed. This movement, of course, effects the drainage of the area undergoing change in level. Where a part of the continent is lowered with respect to sea level, the lower part of streams draining the area are submerged below sea level or *drowned.* The sea enters these valleys and stream erosion ceases. The fine harbors on the Atlantic coast of the United States from Chesapeake Bay to the Gulf of St. Lawrence are drowned river valleys. Similar changes in level produced San Francisco Bay and Puget Sound.

Many places have been uplifted. The immediate effect of the elevation is to increase the gradient of a stream and, therefore, to increase its velocity and erosion power. If such a stream had reached its profile of equilibrium, the equilibrium would be destroyed by the uplift, and the stream would again begin active downward as well as lateral erosion. Such a stream is aptly spoken of as a *rejuvenated stream.* Rejuvenation is caused in other ways also. For example, a stream may have reached a temporary profile of equilibrium based on a lake along its course which has not yet been destroyed. When that lake is drained, the stream above may be rejuvenated. A climatic change that will produce a greater runoff will rejuvenate streams by adding to their volume and thus increasing their ability to erode. Piracy, or the capture of one stream by another, will have the same results. It is not always possible to tell where rejuvenation has been brought about by uplift or by other causes.

Rejuvenation can be recognized by several criteria. If a stream with a flood plain is rejuvenated, renewed vertical erosion will leave the flood plain as a *terrace* on the sides of the valley, well above flood level (Fig. 54). Because of their unconsolidated character, terrace sediments are relatively easily removed by erosion and in many instances have been completely destroyed or exist only as remnants

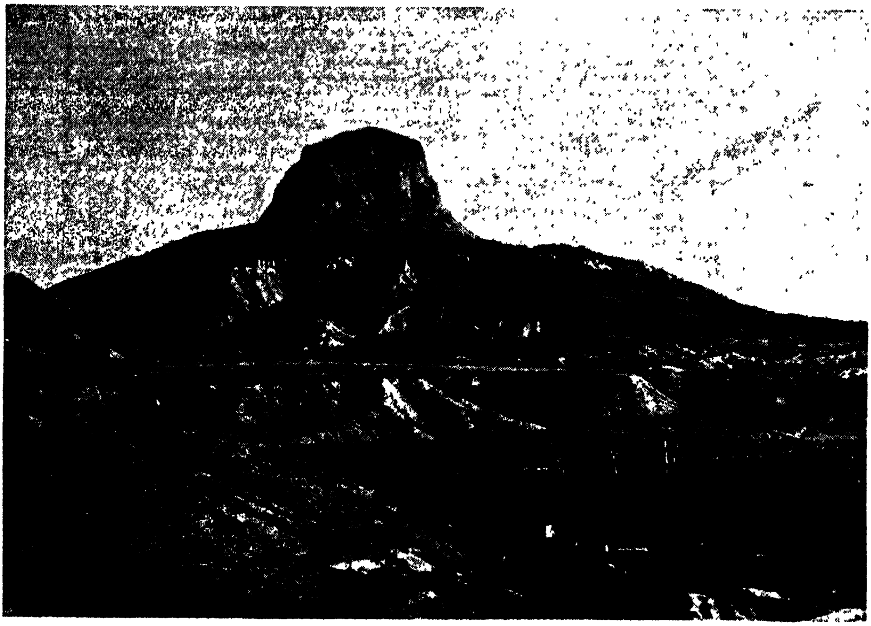

Fig. 54. Rejuvenated stream cut below old flood plain level leaving terrace on opposite side of valley. Volcanic neck in background illustrates differential erosion. Cabezon Peak, New Mexico. ***By W. T. Lee. Courtesy Geological Survey, U. S. Department of the Interior.***

found here and there along the river valley. A valley with gently sloping sides but with an inner gorge in which the stream is flowing is an evidence of rejuvenation. In this case the rock bench at the top of the inner gorge represents the level of the old valley floor, before the stream returned to vigorous downcutting. Yet another criterion of rejuvenation is *entrenched meanders* (Figs. 55 and 56). These are similar in plan to the meanders of the mature or old river, but instead of being cut into flood plain alluvium they are deeply entrenched in bedrock. The meanders were originally formed by a relatively sluggish stream flowing on a flood plain. When the stream was rejuvenated, it began to downcut, but at so slow a rate that it followed its meander pattern. In a relatively short time, the flood plain on which the meanders originated was cut through, and downcutting continued into the underlying bedrock. Sheet wash and tributary

Fig. 55. Entrenched meanders, initial stage. The meandering stream has been rejuvenated and has cut deeply enough below the flats so that deploying of the meander belt across the flood plain is no longer possible. Hoback River, Camp Davis, Teton County, Wyoming. *By W. W. Doeringsfeld.*

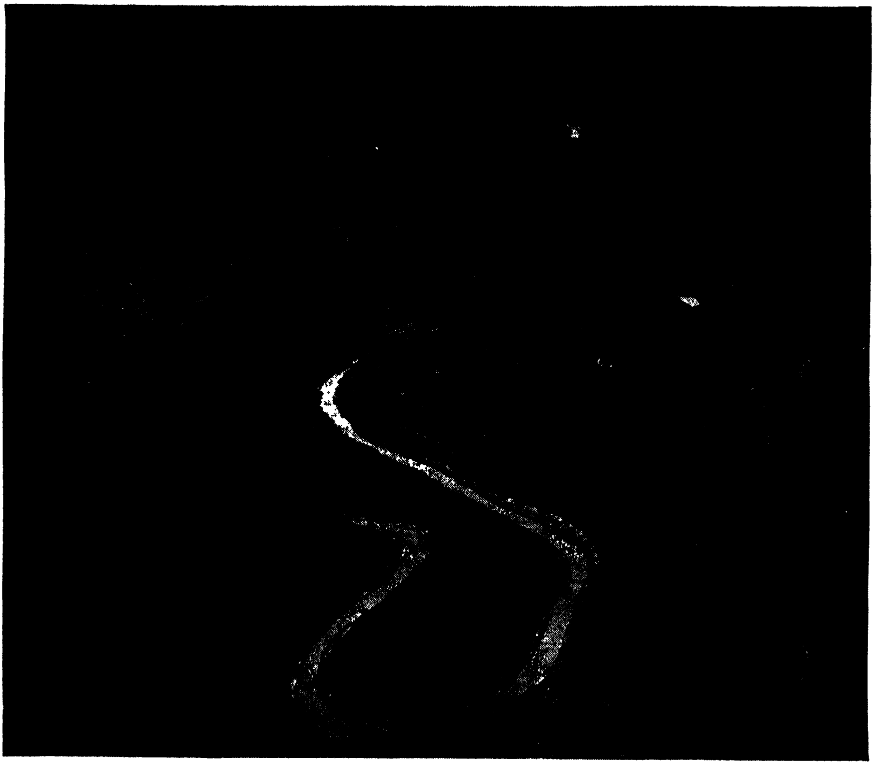

Fig. 56. Entrenched meanders, advanced stage. Lateral planation on outside of loop in left foreground may result in time in the river shortening its course. San Juan River, Utah. *By permission Spence Air Photos.*

streams soon removed all remnants of the original flood plain, leaving the meanders cut in the rock.

CYCLES OF EROSION

A cycle of erosion begins when a land mass is uplifted or built and it closes in such various ways as another uplift, depression below sea level, climatic change, volcanic eruptions. The uplift closes one cycle of erosion and starts a new one. It usually takes place before the land mass has been reduced to a peneplain. However, elevation always starts a new cycle of erosion regardless of the stage of erosion in the interrupted cycle.

Uplift results in the rejuvenation of the streams draining the land mass. Therefore the criteria for rejuvenation given in the preceding section are also cri[illegible]f olde[illegible]sion cycles, but it must be remembered that rejuvenation may result from causes other than uplift.

Where a preceding cycle or cycles of erosion have produced a peneplain, remnants of this surface may be recognizable in an elevated area.

Of course, if the entire uplifted block is peneplained, all evidences of earlier cycles are obliterated, but in many cases only parts of the mass were peneplained before another elevation started a new cycle of erosion, hence remnants of several peneplains lying at different levels may be discernible. As a matter of fact, many regions show evidence of several cycles of erosion. A classic example is the Appalachian Mountain region in eastern Pennsylvania. After diastrophism had created the original Appalachian Mountains, the forces of erosion destroyed them. The accordant summit levels of the present Appalachian ridges are interpreted by some geologists as remnants of this first peneplain. Then, possibly, submergence of the peneplain below sea level resulted in the deposition of coastal-plain sediments on top of the truncated older folded rocks. Gentle arching later raised this region above the sea. Consequent drainage was developed, which became superposed on the underlying rock as the relatively soft coastal-plain sediments were stripped off. This second cycle of erosion produced a second peneplain, which was arched by diastrophism with increase in the gradient of the superposed streams so that they entrenched themselves in the older rocks. The major rivers, such as the Susquehanna, cut across the hogback ridges through canyon-like valleys called "water gaps." During this third cycle of erosion, subsequent tributaries of the superposed streams developed terraces in the weak rocks. Before the intervening ridges composed of resistant rock were destroyed, another elevation rejuvenated the streams so that they incised new valleys below this older erosion surface. Again the weaker rocks were eroded so that further terraces were developed. A relatively recent uplift started the present cycle of erosion. The two younger erosion surfaces are represented today by two levels of terraces; the existence of the older cycles is inferred from the superposed rivers and the approximately accordant summit levels.

The Rocky Mountains, and many other regions, also show evidence of the existence of older landscapes evolved during earlier cycles of erosion. Obviously the geologically recent vertical movement that rejuvenated the streams and caused the sculpturing of the mountain chains of the world into their present form was in reality a series of uplifts rather than a single vertical movement.

RUNNING WATER——ITS EFFECTS ON MANKIND

Running water, as the cause of soil erosion and disastrous floods, is a destructive agent. When utilized for water power, transportation, water supply, and similar purposes, it is of enormous value to mankind. The topography resulting from erosion and deposition by running water has had a decided control on human migrations and on land utilization.

Fig. 57. Gully starting in wagon tracks in a hay field. Indiana County, Pennsylvania. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

Soil erosion. Water running uncontrolled over farm land causes serious damage. In many places, it has been responsible for the removal of the top soil with its permeable structure and rich organic content and for the exposure of the underlying non-fertile rock mantle and bed rock. While soil erosion is taking place in the uplands, good crop lands at lower elevations are being buried under the silt and sand which is being stripped away.

Soil erosion of cultivated land may be caused by the washing of plowed furrows which run down the slope of the land. Each furrow is an incipient valley in which rain wash collects. Where the slopes are steep, the unconsolidated rock mantle is easily eroded. Surface water likewise concentrates in wagon-wheel ruts, and deep erosion results where they run down a slope (Figs 57 and 58). Erosion may be severe also in the master gullies which carry off the surface drainage from a farm (Figs. 59 and 60). Like a river system, occasional water running in these gullies puts out tributaries, and headward erosion by this system often destroys a considerable acreage of farm land. Not only is it impossible to cultivate these badland areas, but the gullies are a hazard to straying stock, and they impede travel about the farm.

Practices which accelerate soil erosion include plowing and planting up and down the slopes, burning the stubble after harvest, overgrazing, and deforestation.

The United States Department of Agriculture established the Soil Conservation Service in 1935 to investigate the increasing wastage of land in this country. Some of the methods recommended by this organization to control wind erosion have been previously described (pp. 52-54) are applicable in retarding excessive erosion by running water. Any method of farming that will conserve moisture in the soil will diminish erosion by both wind and running water.

Some control of top soil erosion can be exercised by a choice of crops planted. Planting of crops in rotation, alternating soil-depleting crops with leguminous crops such as alfalfa that both restore nutrient material to the soil and slow up the movement of water, is recommended. The use of cover crops, such as clover, that are sown or planted in thick stands in order to protect and enrich the soil between the planting and harvesting of two main crops is also advised. One of the purposes of a cover crop is to reduce surface runoff, which in turn prevents excessive erosion of soil; the crop also adds valuable

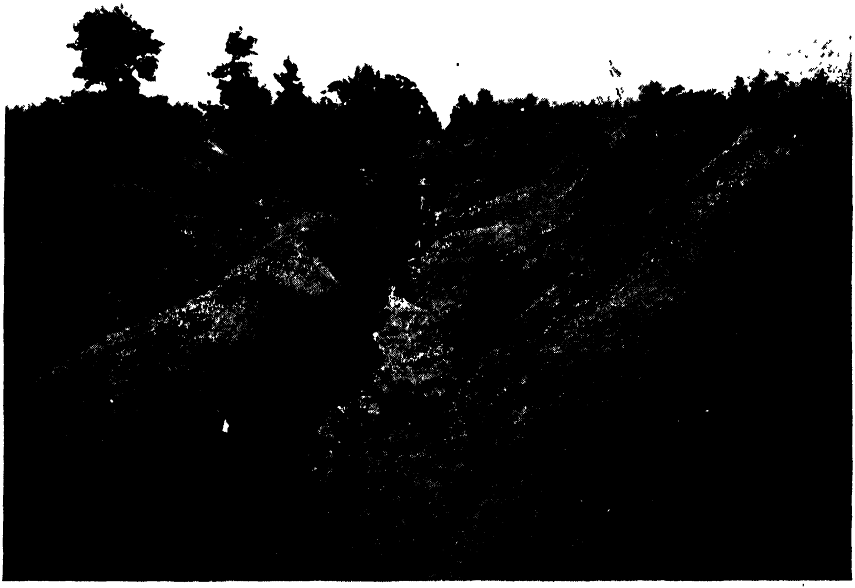

Fig. 58. Large gully in old road bed. Mecklenburg County, Virginia. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

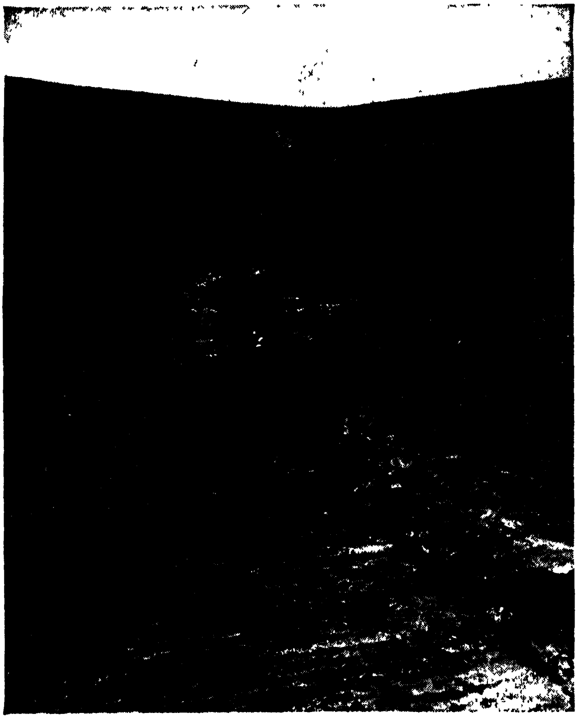

Fig. 59. Result of a 48-hour "gully washer" rain. Umatilla County, Oregon. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

organic matter to the soil and, when plowed under, increases the capacity of the soil to absorb water.

Where sloping ground is being farmed, the Soil Conservation Service advocates plowing and planting on the contour, so that the furrows and ridges will run along and not down the slope. Arranged in this way, they catch water instead of aiding it to run off the land at the greatest possible speed (Fig. 61). Where the slope is steep, contour strip cropping is recommended, which is the planting of alternate bands of clean-tilled crops (planted in rows, with the soil between the rows kept clear of vegetation) and thick-growing crops. For instance, rows of corn may be planted alternately with strips of wheat or oats. Runoff from the clean-tilled strips is caught and absorbed in the thick-growing bands below. Another method of controlling runoff on sloping farms is to terrace the slopes, thereby creating a series of flat surfaces winding around the hill (Fig. 62). This has been done for centuries on the intensively cultivated hill areas of Europe and in

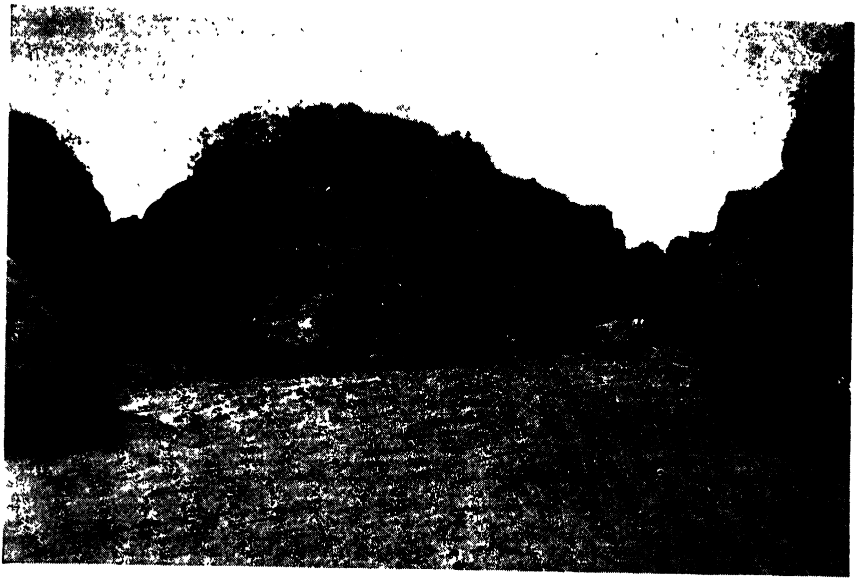

Fig. 60. Every rain increases the size of this enormous gully. Fairfield County, South Carolina. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

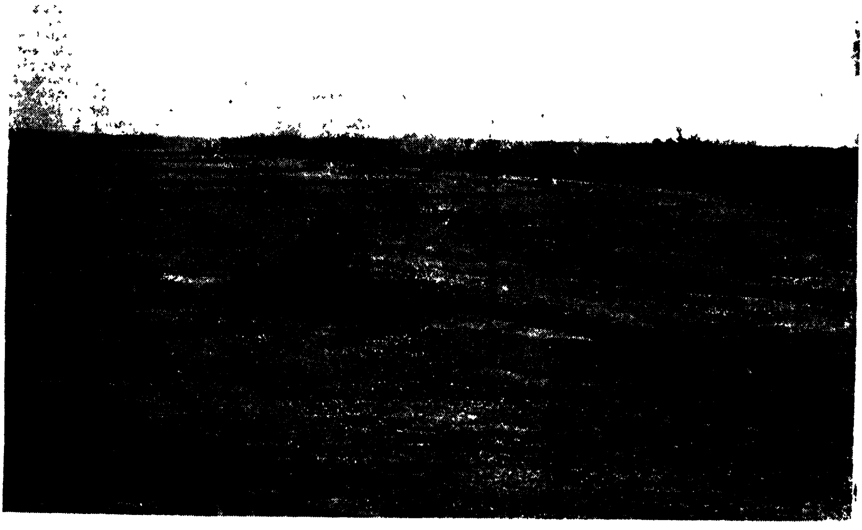

Fig. 61. Contour furrows ploughed in pasture to catch run-off. Oklahoma. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

the interior of China. Mixing crop residues into the soil after harvest changes the structure of the soil so that it becomes more porous to percolating rain water and less easily washed by surface runoff. Even where these various methods are being used, some runoff down the natural depressions already existing in the topography is inevitable. Along such waterways grass cover should be established to prevent further gullying.

Many methods of controlling existing gullies to retard further erosion are described in publications of the Soil Conservation Service. In some cases, a series of dams is built across the floor of the gully. The dams are built of masonry, loose rock, woven wire fence, wooden stakes, tree trunks, or brush (Fig. 63). Another method of gully control is to slope and grade the gully walls and to plant grasses, vines, shrubs, or trees both on the slopes and the gully floors (Fig. 64).

Overgrazed land can be improved by stopping grazing for a period during which alfalfa and grass seed are sown or natural vegetation establishes itself. After the new stand of vegetation has appeared, grazing at a controlled rate may be allowed. Reforestation of deforested areas can be greatly accelerated by systematic tree planting.

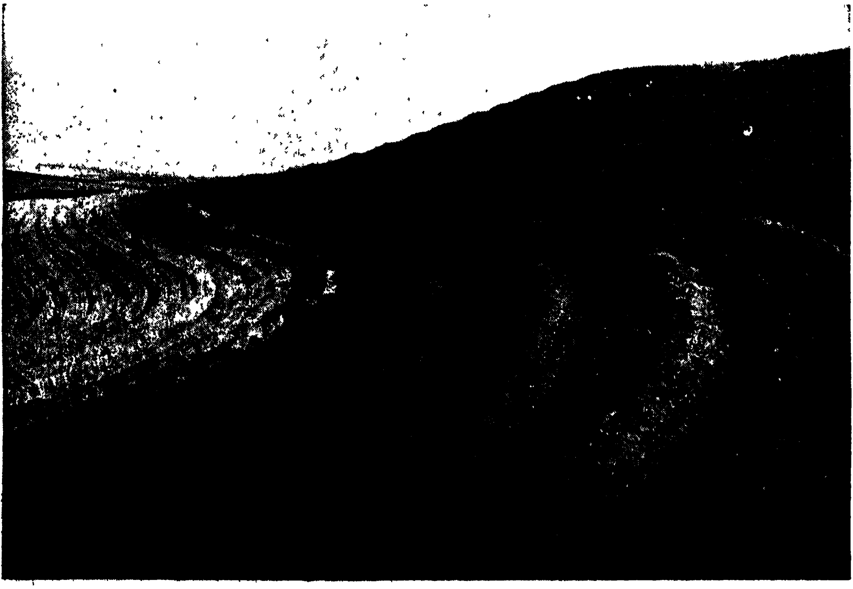

Fig. 62. Terraces built to prevent washing of steep hillside. Trees will be planted in terraced channels. *Courtesy Soil Conservation Service, U. S Department of Agriculture.*

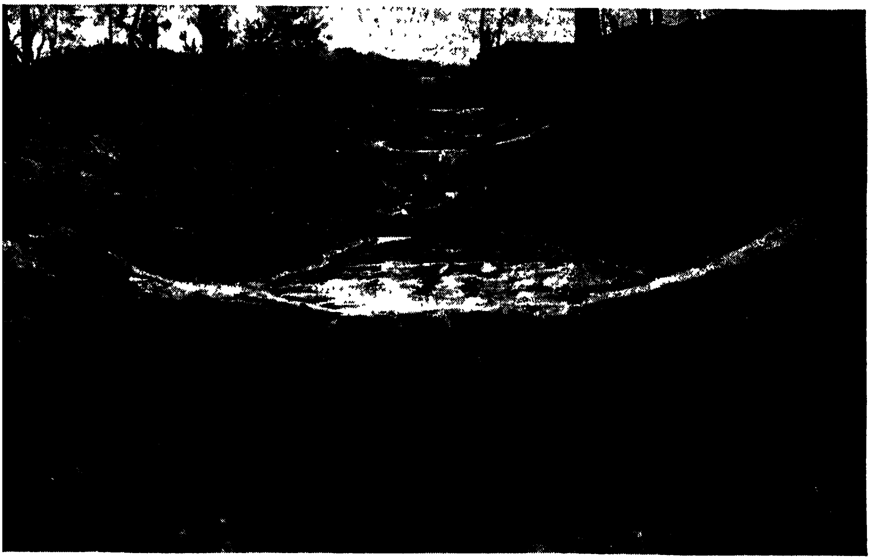

Fig. 63. Series of rock dams built to check gully washing. Near Moore, South Carolina. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

Fig. 64. Abandoned road seeded to prevent gullying. Guilford County, North Carolina. *Courtesy Soil Conservation Service, U. S. Department of Agriculture.*

Floods. Floods are the most disastrous of the natural phenomena. Floods are caused primarily by high precipitation during short periods in a drainage basin. This precipitation may be seasonal, such as that causing the annual floods of the lower Nile and of some of the Chinese rivers, or it may occur at irregular intervals so that a number of years ordinarily intervenes between floods. In some cases, the intervals are of such length that only one great flood has occurred in historic times. Naturally, the speed of precipitation is an important factor, for heavy rain falling during a month will not cause such violent floods as an equal amount falling in a few days.

In the United States, floods are increasing in frequency and magnitude because of the greater runoff resulting from deforestation, overgrazing, and cultivation of areas previously covered with vegetation. Therefore the widespread adoption of practices recommended in the preceding section will not only reduce soil erosion, but will also decrease the frequency and intensity of floods and the damage therefrom. Such measures will also increase the supply of ground water.

Mountainous regions blanketed with thick snow and ice fields may furnish flood waters when a warm wind blowing for several days rapidly thaws the snow and ice.

Disastrous floods have been caused by the collapse of dams, suddenly loosing a great volume of water. In most cases these dams are man-made. They have collapsed because an unusual volume of impounded water following heavy rains has exerted pressure too great for the dam to resist. Structural weaknesses in the dam itself or failure of the rock beneath or at the sides of the dam have facilitated the collapse in some cases.

Natural dams, such as ice and log jams, also impound large volumes of water which may suddenly escape to devastate the valley below. A glacier lying at the headwaters of the Knik River in Alaska dams the mouth of a tributary valley, causing a lake to form. Every few years the lake breaks through the ice barrier, and a wall of water races down the short valley to the sea.

One of the most tragic floods in the United States was that which wiped out the city of Johnstown, Pennsylvania, late in the last century. "On May 31, 1889, after unprecedented rains, a dam across the South Fork, twelve miles above the city . . . gave way, releasing a body of water 60 to 70 feet deep and 700 acres in area. The flood swept down the valley in a mass twenty feet or more in height at its head, at a speed of twenty miles an hour, and within an hour almost completely destroyed Johnstown and wiped out entirely seven other towns in the valley. The Pennsylvania Railroad bridge withstood the strain, and against it the water piled up a mass of wreckage on which many persons were saved from drowning, only to be burned when it caught fire. Between 2,000 and 3,000 lives were lost, out of a population of 30,000, and the loss of property was estimated at $12,000,000."[2] The lower Mississippi valley is periodically flooded, but the greatest flood in the annals of the Mississippi was most disastrous in the valley of a tributary, the Ohio. Early in 1937 swollen tributaries carried into the Ohio the runoff from record rains which had dropped an estimated 60 billion tons of water in the basin during 25 January days. The flood inundated many thousands of square miles, terrorizing people living in eleven states. All river towns were flooded. Paducah, Kentucky, a city of 35,000, was largely under water. Many smaller villages were completely swept away. Some have not been rebuilt, at least not on the same sites. The deaths ran into hundreds, chiefly caused by exposure. Nearly three-quarters of a million people were made homeless. The property damage in one week of destruction was estimated at 500 million dollars. On the aftermath of the flood, we have this picture:

> The flood is over. Now the anxious townspeople can leave their temporary roosts atop the hills on the city's rim. They struggle back to their homes—and to chaos.
>
> The town is soaking under a layer of oozing mud and dripping rubbish. Here beside a grimy piano with swollen, rigid keys lies the carcass of a horse. There stands a splintered telephone pole enmeshed in chicken wire, leaves and straw. Everywhere there is shattered glass, for thousands of windows in town have been crushed by the water's force.
>
> The marching waters have stripped the bridge of its tar-block pavement, leaving a naked super-structure. They have jerked huge slabs of concrete off the highway. They have undermined the sidewalks, either shattering the heavy flagstones or tossing them out of position.
>
> Down the street is the Griffin house—once white, but now, from the ground to the second floor, a muddy brown. Half of the fence around the yard is rusted and distorted; the other half washed away. In front of the house is a pile of tangled wood, a wicker chair, a sofa matted with talc-fine silt, a table, a battered shed. None of the articles belong to the Griffins. Neighbors will drop in soon to claim them.

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[2] *Encyclopaedia Brittanica,* 14th edition, Vol. 13, p. 119. New York: Encyclopaedia Britannica Inc., 1939.

> In the parlor, one of the Griffin boys is playing the hose on the walls and ceiling. The jet of water dissolves a two-inch layer of mud, and a silt-laden stream flows along the ridges of the buckled hardwood floors and out into the hall. Hosing is the only way of throwing off the flood's residue. When the rooms are dry, the plasterer will come in, then the paper-hangers. The carpenter will lay the floors again. The glazier will reset the windows. Finally, painters will burn off the brown collar of the flood's watermark and make the house white once more. This will take about three months and will cost between two and three thousand dollars. The total will be more if the foundation has been weakened.
>
> Outside the town, of course, the waters have carried off not only homes and livestock, but acres of rich, planted farmland as well. Some of this latter has been deposited where the Griffin lawn used to be. There will be no lawn next June: instead will sprout a botanical potpourri of hollyhocks, corn, cabbages.
>
> When the rampant waters of the Ohio or the Mississippi or the Cumberland or the Little Miami fall back below their levees, Mrs. Griffin and her neighbors invariably return to what was once home—though they know that in coming years they will again hear the dreaded cry, "To the hills!"[3]

A combination of heavy rains and melting snows in the headwaters of the Columbia River in the Canadian Rockies in late May of 1948 caused a most disastrous flood in the lower river a few days later. The river reached a height of 14 feet above flood level near Portland, burst through a railroad embankment which doubled as a dike, and covered the city of Vanport, Oregon, with 15 feet of water. The frame buildings of this huge war-time government housing project were floated off their foundations. The number of people made homeless by the flood in Vanport and other communities in northwestern Oregon and southwestern Washington exceeded 50,000.

Many millions of dollars have been spent and will be spent in the future on *flood control* projects. Reforestation retards the flow of water off the mountain slopes in the headwaters of a drainage basin. A system of reservoirs in the tributary valleys may be developed to control the volume of water flowing into the main river, but the system breaks down when one flood closely follows another. Neither method of control is of avail in stemming floods which are due to excessive rainfall in the main valley. The principal method of attempting to control floods is by erecting embankments or levees along the river. By placing these levees back somewhat from the edge of the river a wide channel is provided which may be sufficient to carry off the flood waters. But it is not feasible to erect levees of such magnitude that a "super-flood" will be contained between the embankments. For such floods, spillways and "fuse plugs" are inserted in the levee system by means of which excess waters can be drawn off and large areas of the least valuable land inundated wherever possible.

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[3] Kramer, Thomas, "After the Deluge" (condensed from *Today*), *Reader's Digest*, Vol. 30, No. 180, April, 1937. pp. 14, 15.

Methods of flood control are the problem of the engineer rather than of the geologist. The work of the latter in finding and approving rock for use in retarding erosion of river banks and levee walls is discussed on page 473.

Use of rivers. Water flowing down the bed of a stream has energy, and, throughout historic time, men have used this energy as a source of power. In older days it was the custom to harness a fraction of this power by making the flowing water turn large wheels. Now the usual procedure is to divert the water from a stream, especially above water falls or artificial falls created by the construction of a dam, and then, in some cases after carrying it by pipe or canal for considerable distances, drop it through steep or even vertically inclined pipes, known as penstocks, into the turbines of a power house on the river bank. The turbines turn generators, producing electricity, which may be carried by transmission lines to distant places. Only an extremely small percentage of the potential power of the water that is ceaselessly moving to the sea is utilized. However, the last few years have seen a great increase in generation of hydro-electric power in the United States through the construction of Norris, Hoover, Bonneville, Grand Coulee, and other gigantic dams.

Rivers have been utilized also for the transportation of men and goods. In fact, the exploration of many great areas, including the central part of the United States and the Northwest Territories of Canada, was made possible by river transportation. Rivers have been used in Europe for centuries as arteries of trade and communication. The traffic has been facilitated by the construction of many locks where rapids and falls made passage difficult or impossible and of many canals connecting different river systems. In the United States the construction of thousands of miles of railroad and the ever-increasing demand for speed in travel and transportation has led to a decrease in river traffic except in those rivers which are a part of the Great Lakes waterway.

Rivers, however, have not lost their popularity for recreational purposes. They are extensively used for swimming, fishing and boating, and thousands of people annually visit and enjoy the magnificent scenery of such river valleys as the Grand Canyon.

Most of the larger cities of the world rely upon rivers for municipal and industrial water supplies. Rivers and streams also supply water to many smaller communities and to individuals living along the banks. From the time of the earliest dwellers along the Nile to the present, river water has been diverted for use in irrigation. The great apple-growing district in eastern Washington is irrigated by water diverted from the Wenatchee, Yakima, and other tributaries of the Columbia River, and from the Columbia itself. Similar use is made of many other rivers in the western part of the United States.

A little-known function of rivers is the disposal of human and industrial waste. In developing a large metropolitan area it is highly desirable that an ocean, large lake, or river be available as a means of disposal of waste products.

Effect of physiographic age on farming and routes of travel. Man adapts himself to the physiographic age of his geographic environment. Communication is easiest in old regions, where railroads and highways can be constructed across flood plains and divides alike without encountering excessive grades. The flat plateaus of a region in youth are likewise utilized for lines of communication, but difficulties are encountered where steep-walled valleys and canyons lie across the desired route. In mature regions of great relief, such as mountainous areas, the narrow river flood-plains afford the only feasible route for rail and highway construction. However, if the mature region is one of low relief, it may be possible by much cutting and filling and by detouring around the exceptionally high and low places to project a route across country in any direction.

Late in the 1870's both the Denver and Rio Grande Railroad and the Atchison, Topeka and Santa Fe Railroad sought to reach the new mining town of Leadville in the Colorado Rockies by following the valley of Arkansas River. However, at Royal Gorge above Cañon City the river cuts through a mass of ancient crystalline rock and its valley is a canyon with room for only one line of tracks. Even the one track has to be suspended from trusses (the "Hanging Bridge") at one exceptionally narrow point (Fig. 65). Local tradition has it that the construction crews for the two rival railroads fought for the right-of-way with pick handles; the Santa Fe men won the skirmishes and extended their grade through the Gorge, only to lose it (with reimbursement for construction costs) to the Rio Grande after a protracted series of legal battles which were ended by a Supreme Court decision.

Agriculture is limited in the same way but not to quite the same degree. Other things, such as climate, soil, and market, being equal, the best farming land is to be found in regions of old age where both the flood plains and the low divides can be cultivated. Many regions

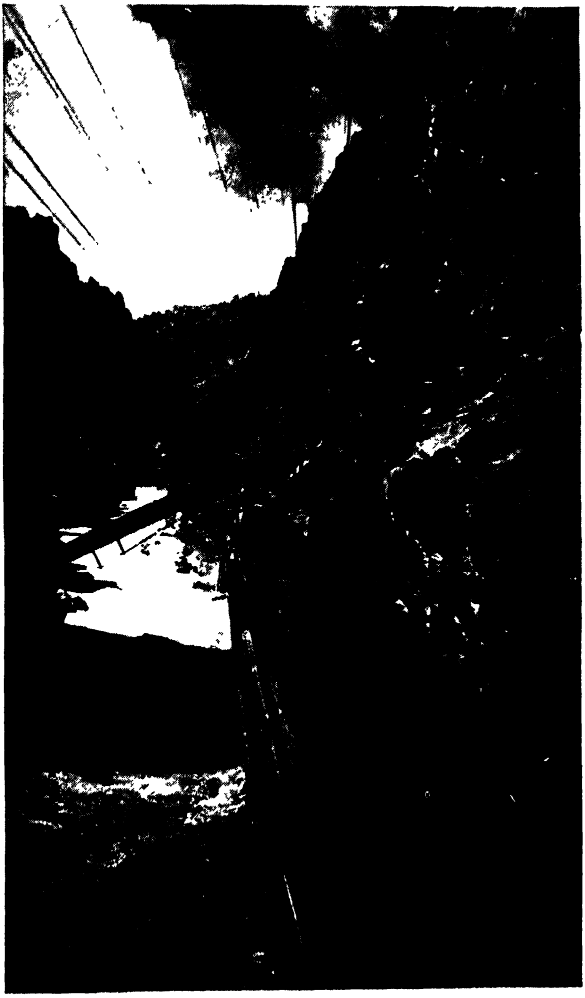


Fig. 65. Hanging bridge in exceptionally narrow section of Royal Gorge, Arkansas River, Colorado. The only feasible route for the railroad was up this youthful valley. *By Kenneth K. Landes.*

in youth are not farmable except along narrow alluvial strips in the valley bottoms because of insufficient precipitation on the uplands and lack of available water for irrigation above the bottom of the valley. Many mature regions are farmed. In mountainous areas are great, natural forests, which support a logging industry. Alluvial terraces, in many instances, make exceptionally fine farm land, for they have all the advantages of flatness and fertility of flood plains, yet they lie at higher elevations and in consequence are not subject to periodic inundation.

In most instances a mature river is much better for navigation than one in old age or youth. The excessive meandering of an old river may make the distances between places excessive, and the occurrence of rapids and waterfalls hinders navigation in a young river. Several towns built on the banks of the Mississippi were subsequently isolated by a change in channel caused in most instances by the cutting through of a meander. Quoting Mark Twain again:

> These cut-offs have had curious effects: they have thrown several river towns out into the rural districts, and built up sandbars and forests in front of them. The town of Delta used to be three miles below Vicksburg; a recent cut off has radically changed the position, and Delta is now *two miles above* Vicksburg. Both of these river towns have been retired to the country by that cut-off.[4]

[4] Op. cit., p. 3.

CHAPTER 6

Ice as a Geologic Agent

THE IMPORTANCE OF WATER'S FREEZING in rock and soil and causing disintegration by expansion during crystallization was discussed as a phase of mechanical weathering (p. 23). With this exception, ice is not a very important geologic agent except in regions where glaciers are present. River ice moves downstream with the spring thaw and transports a small number of rock fragments frozen to it. The ice blocks sometimes jam together to form a temporary dam which, unless it is soon destroyed by blasting, may impound a large body of water. Such dams are weak and eventually give way, releasing floods which cause great damage to farms and communities downstream. Lake ice may push up on the shore and shove the beach sand and gravel into mounds, known as "ramparts," paralleling the edge of the lake. They are described and illustrated in Chapter 8.

During certain periods of the past, when temperatures fell below normal over large areas of the earth, great sheets of moving ice called *glaciers* covered large areas and considerably altered the topography of the regions over which they advanced. It so happens that the last "Ice Age" or Glacial Period was so recent, as geologic time is measured, that its effects are still readily observable in the glaciated areas. These are to be found on all continents but especially (due to greater land areas in the higher latitudes) in the Northern Hemisphere. In many mountainous areas, and in Greenland and Antarctica, remnants of Ice Age glaciers still exist. For this reason we can study the work of glaciers directly and infer from it what has taken place in regions from which glaciers have disappeared.

GLACIERS

A glacier is a mass of slowly flowing ice. The first step in its formation is the accumulation of a permanent snow field. The lower layers of the snow turn to ice through the re-freezing of snow temporarily liquefied under pressure, and through the condensation and freezing of moisture attempting to escape by evaporation. In a relatively short time, a thick body of snow changes from an incoherent aggregate of light snowflakes into a dense mass of crystalline ice.

Types. Glaciers are of four types: *valley, piedmont, plateau,* and *continental.* Valley glaciers occupy mountain canyons that have been cut by rivers. They move down the valleys as the rivers do, but with much less velocity. The mountain ranges of the world contained many valley glaciers during the Glacial Period, and as already stated, the higher mountains of the temperate zones, and much lower mountains in the polar areas, have valley glaciers today. Valley glaciers, because they follow the winding valleys of preexistent rivers, are tortuous and many times longer than wide. The largest valley glaciers are in Alaska where the combination of fairly high latitude, lofty and extensive mountain ranges, and heavy precipitation offers ideal conditions for abundant accumulation of ice. Within the boundaries of the United States proper, the largest group of valley glaciers is on Mount Rainier, a great dormant or extinct volcano in Washington. On this mountain, there are 24 glaciers from seven to fifteen miles long which descend from the great snow-ice fields at and near the summit of the peak. One of the largest valley glaciers in the world is the Beardmore, which extends from the ice cap on the Antarctic Plateau to the Great Ice Barrier on the coast. This ribbon of ice is 125 miles long and from 10 to 20 miles wide.

A piedmont glacier is formed by the emergence of a valley glacier upon an adjacent lowland. Not infrequently a number of piedmonts unite to form an apron fronting the mountain range from which the valley glaciers come. Glaciers of this type are unimportant except in Alaska where the topographic environment is favorable. However, during the Glacial Period, many piedmont glaciers existed even in what are now temperate latitudes.

The accumulation of ice in a dome-like, outward spreading mass on a high plateau produces a plateau glacier. The surface of such a glacier does not reflect the configuration of the underlying rock floor, thus differing from mountain valley glaciers. However, tongues of ice extending outward from the margin of a plateau glacier may follow preexistent valleys and therefore can be classified as valley glaciers. The best known examples of plateau glaciers are in Norway.

Two great regions, Greenland and Antarctica, are largely covered by continental glaciers or ice sheets. These glaciers have a broadly domed surface, and their form is quite independent of local topography. The Greenland glacier covers all of that great island except a mountainous belt along the coast which is five to twenty-five miles wide. But large as is this ice mass, it is dwarfed by the glacier capping Antarctica, which has an area of about 5,000,000 square miles. The average thickness of the Antarctic ice is several thousand feet.

During the Glacial Period, continental glaciers in North America and Eurasia were many times larger than the Antarctic ice mass.

Origin. The conditions necessary for the existence of glaciers are (1) temperatures most of the time below freezing and (2) abundant precipitation. The former condition is met by high latitude or high altitude, or both. Without abundant precipitation glaciers will not form even though temperatures are low, for snow and ice in a thin blanket, instead of accumulating into a glacier, will disappear through melting and evaporation. The high mountain chains in Alaska, British Columbia, Washington, and Oregon, bordering the east side of the Pacific, are well watered by the prevailing westerly winds, so they are ideal places for the formation of glaciers.

However, there is abundant evidence, including both glacial erosion and deposits, that during certain past epochs continental glaciers pushed into what are today temperate latitudes, that valley glaciers extended much lower in mountain canyons than they do now, and that they were present in mountains which are now ice free. During the recent glacial period the snowline (limit of perpetual snow) averaged about 4,000 feet lower than it is today. Obviously, these periods of expanded glaciation resulted from temporarily lowered temperatures.

Movement. The movement of valley glaciers has been likened to the movement of a river, but there is little actual similarity between the two beyond the fact that each flows down a valley. Glaciers are brittle solids which flow under pressure but which crack and break open upon passing over uneven places on the valley floor. Because of their rigidity, glaciers can move uphill where there is sufficient ice to overflow the obstacle. Rivers, of course, neither crack open nor run uphill. A continental glacier moves outward from its point of origin, where high precipitation has caused snow and ice to accumulate to such great depths that an outward sloping surface is produced regardless of local topography. The principal movement of ice in a continental glacier apparently is confined to the marginal zone.

The movement of ice involves more than simple sliding. Probably the most potent force is freezing and recrystallization. Ice at the surface thaws under the heat of the sun, and more deeply buried ice may liquefy due to the pressure upon it which lowers the melting point. Some of the melt water may escape from the glacier by evaporation and run-off, but part percolates into sections of the ice mass where the temperatures are below the freezing point, even at the pressure existing there. This water refreezes. Because water expands upon freezing, pressure is exerted where this change from liquid to solid is taking place and movement will result. The principal movement is in the direction of least resistance, which is down slope. The relative importance of movement through recrystallization is shown by the behavior of modern valley glaciers, which move much faster during the relatively warm summer months when melting is at a maximum.

The rate of flow of several modern glaciers has been obtained by driving stakes across the surface of the ice and determining the position of the stakes with surveying instruments from time to time. Some glaciers move but a few inches a day, while others move several feet. The central part of the Mer de Glace in the Alps moves at the rate of 27 inches daily. In 1820 three guides attempting to ascend Mont Blanc in Switzerland were caught in an avalanche and buried in the ice of a valley glacier. A scientist well acquainted with the rate of flow of Alpine glaciers predicted that the bodies would be recovered at the terminus or *foot* of the glacier in a period of 35 to 40 years. Forty-one years later the bodies appeared, after having travelled nearly 10,000 feet at an average rate of about 8 inches a day.

Glaciers are analagous to rivers in that the rate of movement is not the same at all points. A valley glacier, like a river, moves at a faster rate in the middle than at the sides, so that a row of stakes driven across a glacier in a straight line soon has a decided curve downstream. The central part of the glacier moves faster probably because it is not retarded as much as the sides by friction of the valley walls. Lack of friction also allows the upper part of a glacier to move faster than the ice near the valley floor.

Where mountains in high latitudes lie near the coast, many valley glaciers extend down to the sea and even out into it for short distances (Fig. 66). Glacial ice can exist below the snow line because it is constantly replenished from the great snow and ice fields which lie at the valley head. The lower limit of a valley glacier depends upon several factors. One is the size of the glacier. The greater the volume of ice, the farther it can flow into the areas of higher temperature, because of the greater quantity of ice to melt. The speed of motion is also a factor. Other things being equal, the faster the glacier moves, the farther down the valley it can advance. Of prime importance, of course, are the temperatures encountered in the lower valley. Glaciers occupying the valleys in the mountains of the Alaskan coast can extend to the sea because of the relatively low average temperature at sea level. The glaciers on the south side of Mount Shasta in California descend to an elevation of 11,000 feet, while on the north side, where the average temperatures are lower, they extend to an elevation of about 9,000 feet.

Glaciers are spoken of as "advancing" or "receding." These terms

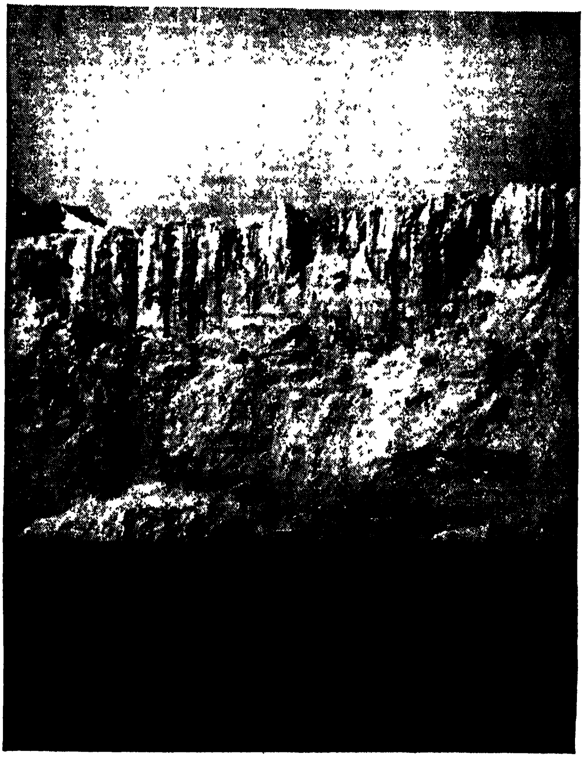


Fig. 66. A glacier goes to sea. Childs Glacier, Alaska. *By Henry Landes.*

apply, of course, to the foot of the glacier. If the melting at the foot exactly balances the forward movement of the ice, the lower end is stationary, but, if the ice moves forward faster than it melts, the foot advances. A glacier near the Copper River Railroad in Alaska has advanced several different times since the tracks were laid, imperiling the narrow space available for the road. A receding glacier is one in which the ice at the terminus is melting back faster than the glacier is moving forward (Fig. 67). This does not mean that the glacier itself is moving back up the valley. The Nisqually glacier on the side of Mountain Rainier has receded several thousand feet during the last forty years. As a general rule, valley glaciers in the temperate zone have receded since they were first observed, but a number of glaciers in more northern latitudes have advanced during the same period.

Features of valley glaciers. The glaciers that occupy the mountain and high latitude valleys of today have a number of common features. They are invariably crossed by great fractures. The sides and foot of each glacier are dark in color, because of soil and rock frozen in the ice. A stream of water emerges from the foot of the

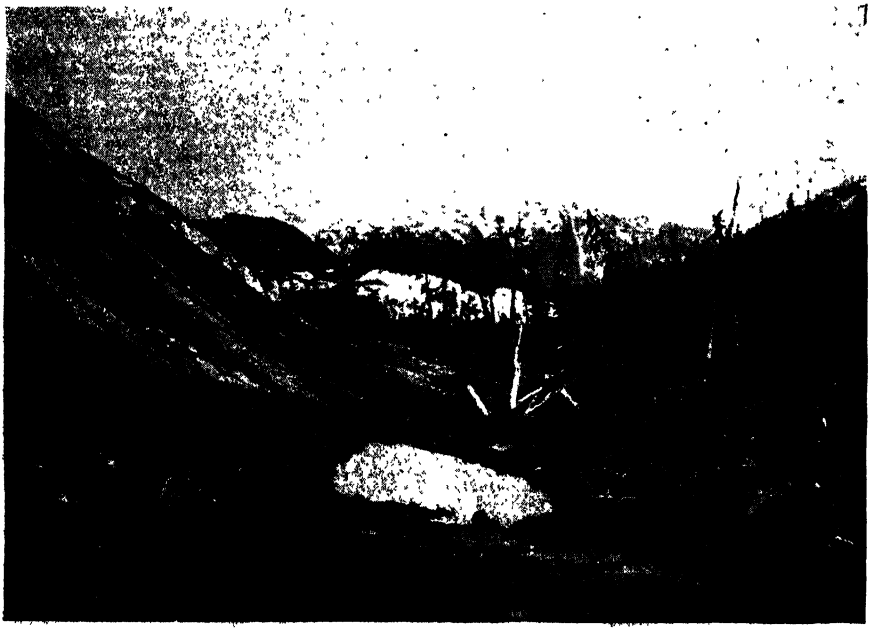


Fig. 67. Receding glacier on left; ice-destroyed forest on right. Columbia Glacier, Alaska. ***By U. S. Grant. Courtesy Geological Survey, U. S. Department of the Interior.***

glacier; in fact, some mighty rivers have melting glacial ice as their sources.

The cracks, or *crevasses,* that develop in glaciers result either from irregularities in the valley floor or from different rates of movement in different parts of the slowly flowing ice mass. Toward the foot of a valley glacier, the direction of the crevasses roughly parallels the valley, because of the tendency of the glacier to spread laterally at its lower end. Farther up the valley, the crevasses run across the glacier more nearly at right angles to the valley walls.

A glacier picks up and carries dirt and rock. These ice-transported materials are referred to as *moraine.* Because of the down-valley movement of the ice, the morainal debris is carried to the foot of the glacier where it accumulates, forming *terminal moraines,* as the ice melts. The morainal materials accumulating at the sides of a glacier form *lateral moraines.* Where two glaciers merge at the forks of a valley, their inside lateral moraines coalesce to form a *medial moraine* which lies out near the middle of the glacier below the forks. Although these moraines are dark in color and appear from a distance to consist solely of rock and debris, examination shows them to be ice containing scattered rock fragments of varying sizes from pebbles to boulders. The term "moraine," with its qualifying adjectives denoting position, is also applied to the rock debris after the ice has dropped and abandoned it by melting and evaporation.

Whenever the temperature rises above the freezing point, the exposed ice of the glaciers begins to melt. On warm days, water is formed in considerable volume throughout the length of the glacier and creates and feeds a multitude of streams that have their channels on top, within, or beneath the ice. Because of the crevassed character of the glacier surface, streams in most cases do not travel very far on top of the ice but tumble down a crevasse into the ice to follow a lower channel. The lower terminus of a valley glacier may have many streams emerging from the ice at different points and, farther down valley, coalescing into one big river. A large quantity of water also issues from the sides of the glaciers next to the valley walls. The volume of water emerging from a glacier varies enormously between winter and summer, and even between night and day. A few glaciers terminate, at the present time, in a lake (Fig. 68).

Observations of present valley glaciers, together with observations made of the relatively small continental glaciers existent today, permit us to interpret the record left by the tremendous glaciers of the past. Geologists believe that the continental glaciers were crevassed in the marginal zone at least, where movement was taking place. They were completely encircled by terminal moraines. Lateral moraines did not exist, except along the sides of tongues which projected out from the main ice mass. The amount of water discharged from the continental glaciers was enormous, especially where ice sheets reached relatively low latitudes. This water issued forth from countless points about the periphery.

HOW GLACIERS WORK

Like wind and running water, glaciers are important agents of erosion and deposition, but the mechanics of the processes are quite different.

Erosion. Glacial erosion is accomplished mainly by *plucking* and *abrasion.* Glacial ice freezes onto a joint block (a mass of rock which has been loosened by jointing) and, as the ice moves onward, "plucks" or quarries out the block and carries it along. A valley glacier erodes by plucking at the head of the valley, where it is constantly pulling away from the mountain side, and from the valley walls and floor. Plucking by a continental glacier is confined to the floor. A glacier, riding over a bed-rock hill, does not pluck from the "upstream" side to any great extent, because the hill itself blocks the removal of the rock; but on the "downstream" side, where the hill slopes in the direction of glacial movement, the ice commonly freezes onto a jointed block of rock, pulls it straight out, and carries it away. Because of this plucking, glaciated bed rock hills have their steeper slopes, as a general rule, on the side toward which the ice moves.

Ice alone is softer than rock, hence it cannot abrade without tools. The abrasives used by moving ice are rock fragments, whose edges protrude from the bottom or side of the glacier and abrade or wear rock with which they come in contact. Glaciers also remove loose debris which is pushed ahead by the advancing ice front.

Transportation. The rock load is transported in many cases for great distances by the moving ice. Most of the load is carried near the bottom of the ice and, in valley glaciers, along the sides.

Valley glaciers receive showers of sliding and falling rock from the steep valley walls above; at first the fragments are carried on the top of the ice, but later much of this debris works its way downward into the ice. The streams emerging from the front of a glacier are loaded with detritus, which they may transport far beyond the margin of the ice. Although this material is transported by running water, it may properly be considered a by-product of glacial activity, because both the water and the detritus come from the glacier.

Deposition. The material transported by glaciers eventually is deposited by the dropping of debris under the ice as it moves forward, by emergence at the end of the glacier, and by abandonment when the ice melts. Deposition under the ice occurs when rock works its way chiefly along crevasses through the ice until it reaches the floor over which the ice is moving. It may then be dragged along and dropped when the surrounding ice melts, or it may constitute too big a load to be carried farther, so that the glacier overrides it.

A glacier is continuously bringing material to its lower end, where it is deposited when the ice melts. Therefore the debris scattered through a glacier is destined to be deposited at its foot or, in a continental glacier, along its margin.

The disappearance of a glacier causes deposition of all the material in the ice. Even though the glacier front may be retreating, there nevertheless is forward movement of the ice until the glacier attains the last stages of stagnation. Therefore, as the ice melts, additional debris is brought forward, so that a thicker veneer of material is deposited than would be by the melting of a stationary mass of ice.

The rock fragments carried away from the ice by sub-glacial streams is deposited principally during the waning of flood waters. Much of this sediment is so finely ground by the glacier that it is carried to the sea before being deposited.

EROSION BY VALLEY GLACIERS

Erosion by valley glaciers has caused the removal of great volumes of rock and has produced various changes in topography. Some of the land forms are readily recognizable and can be used to prove the past existence of glaciers. Glacial erosion has produced unique features of great scenic charm, which are enjoyed by thousands of people each year.

Cirques. The gap formed at the upper end of the reservoir ice of a valley glacier as the ice pulls away from the head of the valley in its forward movement is intermittently filled with snow. This snow turns to ice, thereby becoming a part of the upper end of the glacier. Each time the ice pulls away from the valley head, it carries with it loosened joint blocks. By this quarrying or plucking, the valley head is gradually deepened and widened to form a steep-walled amphitheater, known as a *cirque* (Fig. 68). Basins are commonly excavated in the bottom of the amphitheater. Many small but extremely beautiful mountain lakes occupy cirques made by glaciers thousands of years ago.

A mountain peak girdled by ice-filled cirques may develop the steep flanks and pyramidal shape for which the Matterhorn in the Swiss Alps is famous. Such peaks are called *horns* (Figs. 69 and 70). The quarrying action at the heads of two glaciers on opposite sides of a divide may produce a gap or *col* (Fig. 71) in the ridge which is analagous to the pass formed by headward erosion of opposite flowing streams.

Glaciated valleys. Valley glaciers so change the form of mountain canyons that their presence can be proved long after ice has melted away. The normal mountain valley eroded by rivers is V-shaped, the sides converging at the valley floor. Glacial plucking

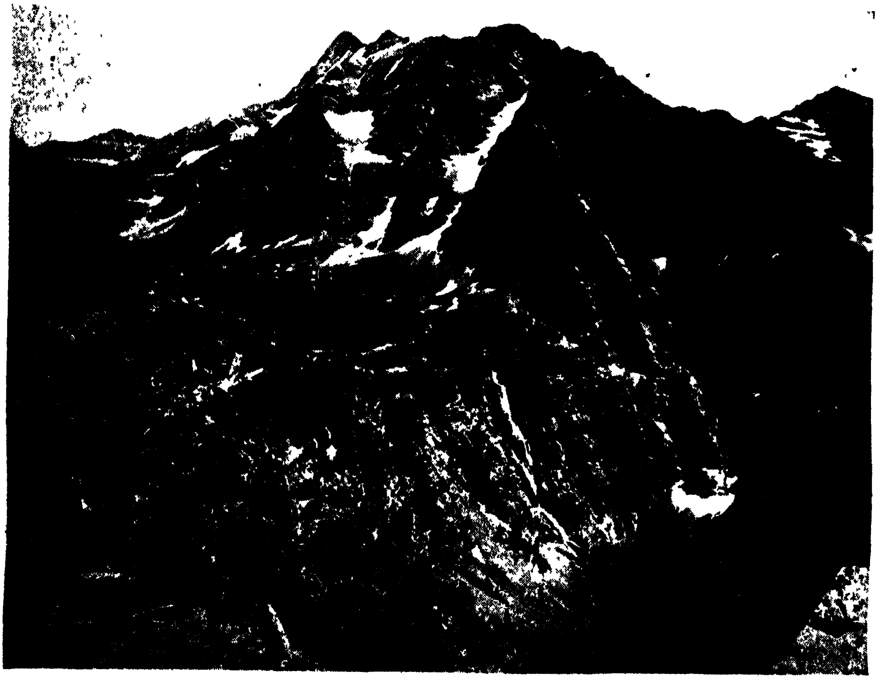


Fig. 68. Cirque and cirque lake (Lake Ellen Wilson). Peak in center background is Mt. Jackson; low pass or *col* visible in background at upper left. Glacier National Park. *Photo by Hileman. Courtesy National Park Service, U. S. Department of the Interior.*

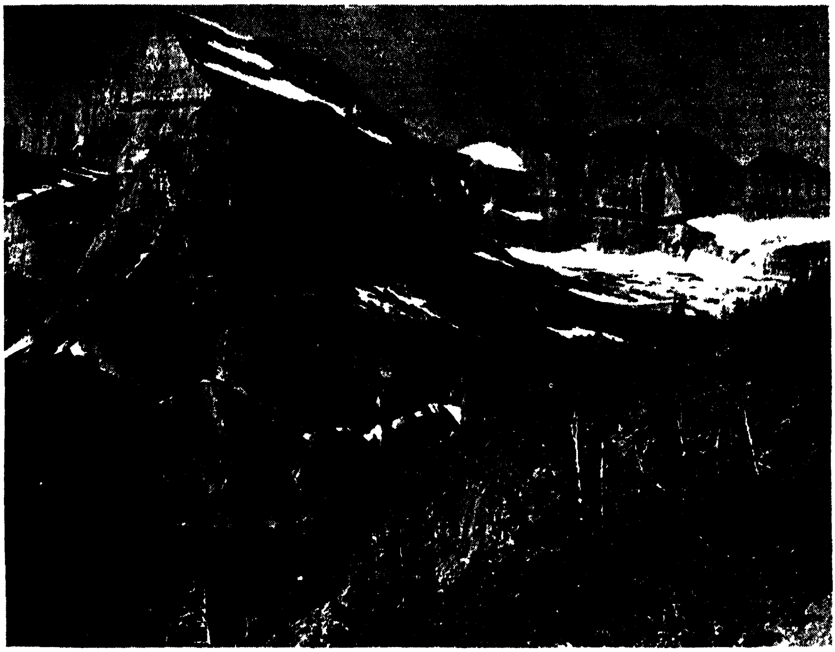


Fig. 69. Mt. Gould, a horn in the making, at upper left. At least one of the characteristic pyramidal faces has been completed. Grinnell Lake on left. Glacier National Park. *Photo by Hileman. Courtesy National Park Service, U. S. Department of the Interior.*

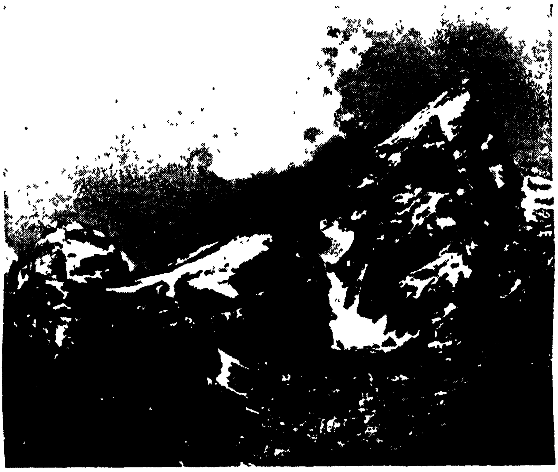


Fig. 70. Horn at upper right. Grand Teton National Park, Wyoming. *By M. V. Denny.*

and abrasion steepens the sides of the V-shaped valley, making it U-shaped (Fig. 72). They also widen and straighten the valleys. In most glaciated valleys a "shoulder" high up the valley side is visible, marking the break between what is left of the old V-shaped valley and the present U-shaped valley, and showing the depth to which the valley was formerly filled with ice. Many instances are known where valley glaciers have scooped out their floors to great depths. Lake Chelan occupies a glaciated valley of this type on the east flank of the Cascade Range in the state of Washington. The surface of the lake is at an elevation of about 1,000 feet, and the lowest point on the inundated glaciated valley floor, where the lake is more than 1400 feet deep, is over 400 feet below sea level.

Another recognizable feature of glaciated valleys is the truncation of *spurs*. In ordinary valleys the divides between the tributaries project into the valley in tapering points, or spurs. A glacier moving down such a valley truncates the points so that the valley wall between tributary valleys becomes *faceted* into triangles (a facet is a geometric face, as on a cut stone). Two parallel and contiguous glaciated valleys may be separated by a knife-edge ridge called an *arête* (Fig. 73).

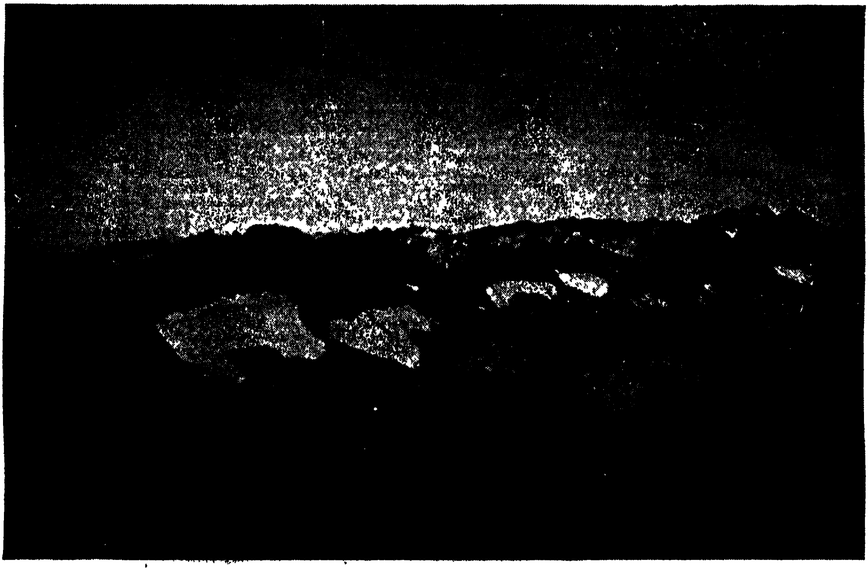


Fig. 71. Glaciated divide, with series of gaps or *cols* formed by headward erosion of cirques. Middle Palisades, High Sierras, California. *By permission Spence Air Photos.*

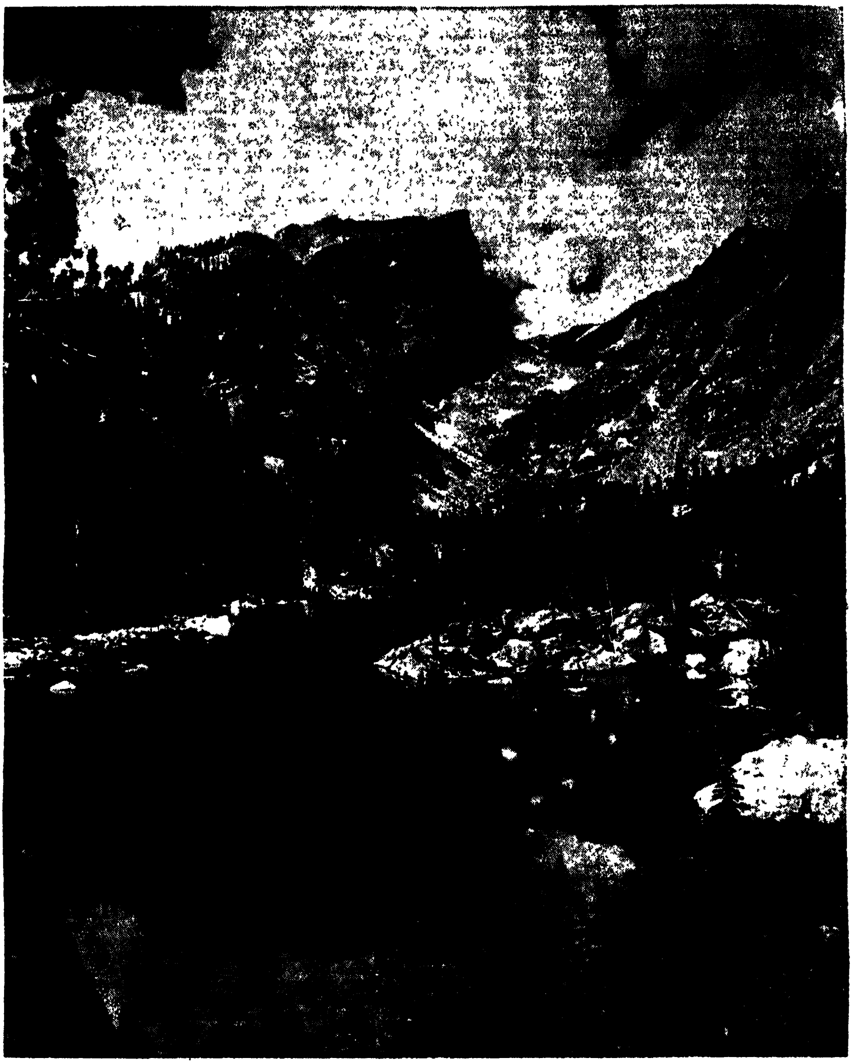


Fig. 72. Steep-walled, U-shaped glacial valley. Hallett's Peak in center background. Bear Lake in foreground. Rocky Mt. National Park, Colorado. *Courtesy Union Pacific Railroad.*

Hanging valleys may be created by valley glaciation. In this case the tributary valleys have been cut back to a point where they are not as deep as the main valley. As a result, they "hang" high up on the sides of the main valley, the streams in the tributary valleys joining the main river through a series of falls and cascades (Fig. 74). Hanging valleys are caused through deeper scouring by the glacier occu-

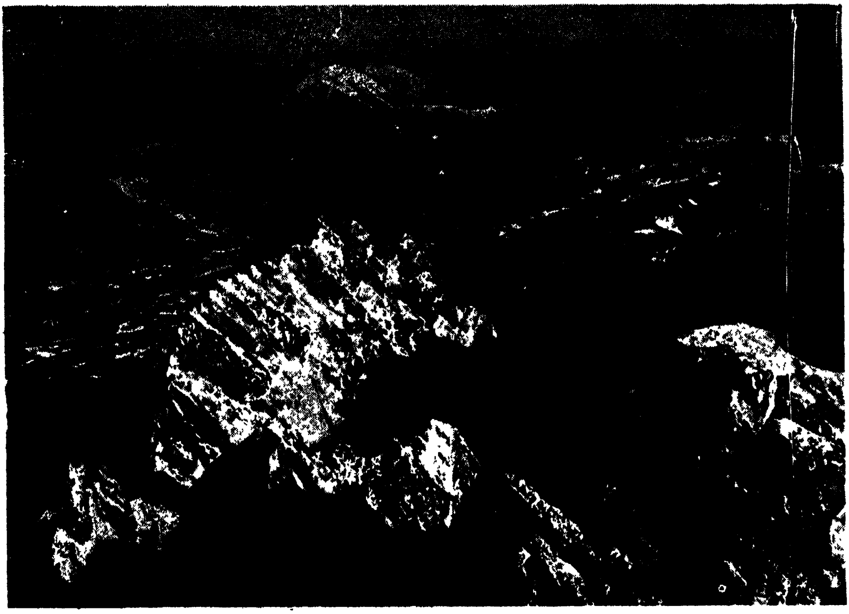


Fig. 73. An arête, or knife-edge ridge, between two glaciated valleys. Zugspitz, German Alps, looking toward Partenkirchen. *By Luis de la Torre.*

pying the main valley. The tributary valleys may likewise have had glaciers, which were unable to excavate as deeply as the main glacier.

DEPOSITS OF VALLEY GLACIERS

Occurrence. During their life time, valley glaciers deposit part of the debris which they carry, and all of it is dropped when the ice disappears. Deposition is confined to the floor of the valley, where, after the ice has left, some or even all of the unconsolidated glacial sediment may be removed by streams. The general term applied to the various types of deposits resulting from glaciation is *drift,* which is another form of transported rock mantle. Like wind and stream deposits, it covers the bed rock over wide areas.

Drift is of two types: unstratified, or *till,* and stratified, or *glaciofluvial drift.* Till is deposited by and from a glacier without the aid of running water. Unlike wind and running water, moving ice does not sort the material which it transports and deposits. Small particles of clay and large boulders commonly are deposited together; therefore, deposits of till are not stratified as are other types of sedimentary rock.

Glaciofluvial drift is sediment deposited by a glacial stream, either beneath the ice or beyond its borders. Since these deposits are formed by running water, they are sorted and stratified.

Drift deposited by a valley glacier may be recognized in several ways. Its topographic position at or near the valley bottom is indica-

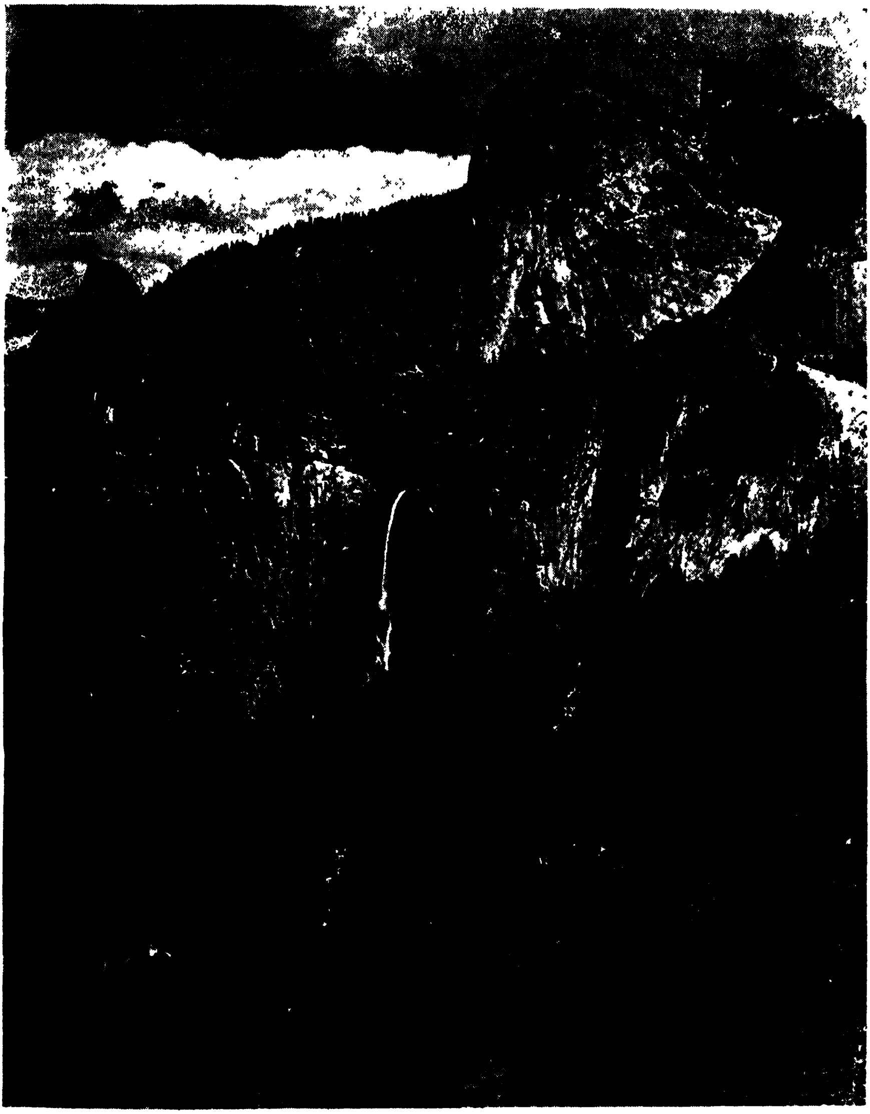


Fig. 74. Water falling from lowest point of hanging tributary valley to floor of glaciated main valley. Yosemite National Park. *Courtesy U S. Department of the Interior.*

tive of its origin, and the different types of drift deposits have characteristic shapes that will be described in the following paragraphs. The material in the deposits consists of unstratified till, and the coarser pebbles, cobbles, and boulders generally are much more angular than those rolled down a stream bed by running water; transportation in a glacier commonly results in the rounding of the edges and corners of rock fragments, producing *subangular* shapes. In addition, some of the fragments are scratched or *striated* as they rub together in the drift or scrape against the floor of the valley.

Till deposits of valley glaciers include various types of *moraines,* and *valley trains* result from glaciofluvial deposition. The morainal deposits are named according to their positions in respect to the glacier.

Terminal and recessional moraines. The most prominent moraines left by valley glaciers are the terminal and recessional moraines, which commonly extend from wall to wall across the valley. They are very irregular, ridge-like masses of glacial till. A *terminal moraine* consists of material, originally scattered through the glacier, which was brought down to the end of the glacier where it was released by melting. In general, the longer the lower end of a valley glacier is stationary, the greater is the size of the terminal moraine, because much more debris will be brought forward and deposited.

A receding glacier does not retreat at a constant rate. There are periods when the edge remains stationary or even advances for a short distance. Moraines are built at the foot of a receding glacier whenever that edge remains stationary for any length of time. This type of terminal moraine is called a *recessional moraine,* since it lies behind the terminal moraine.

Lateral moraines. The melting of a valley glacier causes the deposition of rock fragments in low ridges along the valley sides. These are called lateral moraines.

Ground moraine. As a valley glacier recedes, the debris in the ice mass is let down onto the valley floor as an unstratified deposit so unequally distributed that it has a hummocky surface.

Valley trains. The water that flows out from the foot of a valley glacier scatters sediment down the valley for a considerable distance, building a type of flood plain known as a *valley train.* With the recession of the ice, glaciofluvial sediment will continue to be deposited, in many cases on top of earlier-deposited ground moraine.

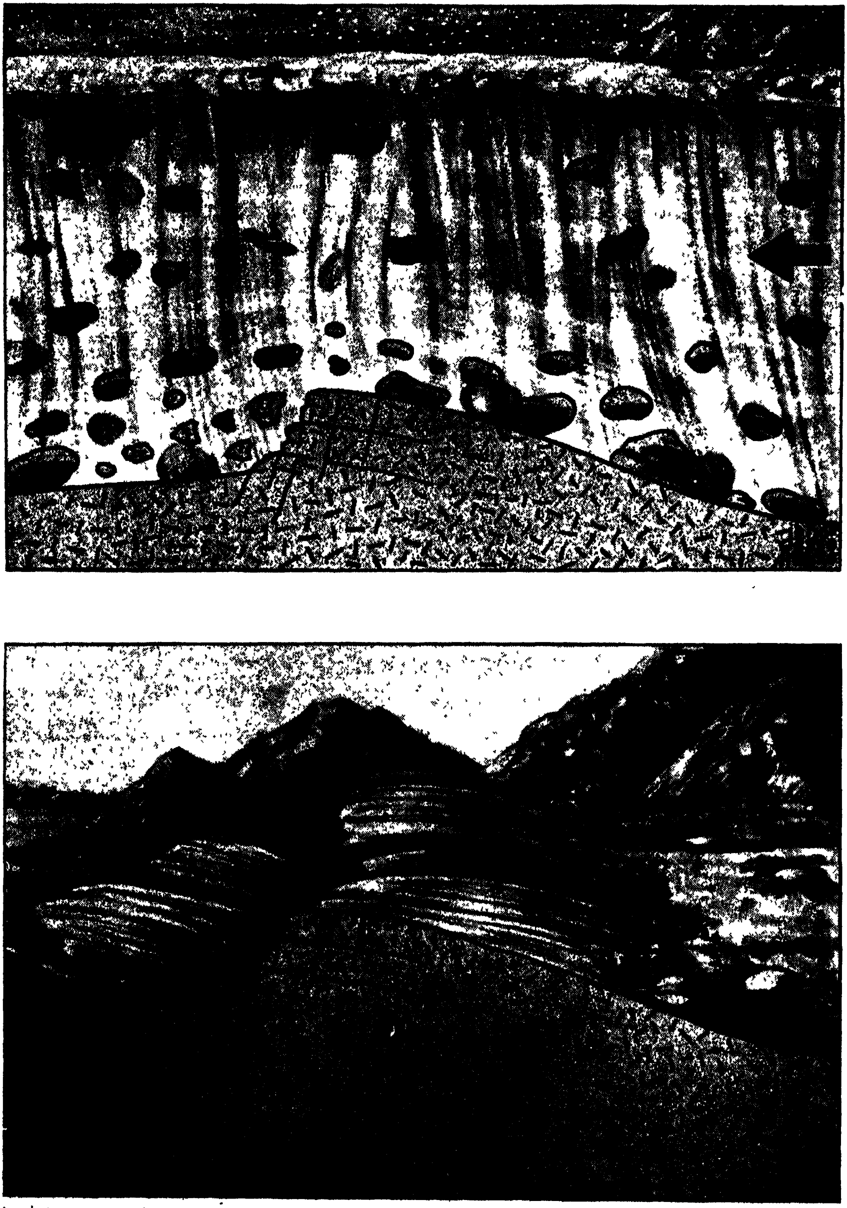
EROSION BY CONTINENTAL GLACIERS

Denudation. Continental glaciers are very active eroding agents, plucking debris and abrading rock surfaces over wide areas. Most of the material removed is mantle rock, as it is most easily lifted, but there also is vigorous attack on bed rock (Figs. 75A and 75B). The two largest of the North American ice sheets during the recent Ice Age had their centers just west and east of Hudson Bay; in central Canada today, the soil mantle is very thin and in places missing, over thousands of square miles. While continental glaciers denude great areas of soil cover, much of the material removed is subsequently deposited near the margin of the glacier.

The direction of movement of glacial ice over bed-rock surfaces can be determined by the presence of *striations,* roughly parallel scratches or grooves made by protruding edges of rocks carried near the bottom or side of a glacier. The direction of the striae give the direction of movement of the glacier at a particular point.

Striations and grooves are abundant on the bed-rock floor over which the North American ice sheets passed (Figs. 76 and 77). The ice also scoured out in the bed rock a multitude of depressions which are now filled with water. Hills overridden by the ice were smoothed off on the side from which the ice came and were steepened by plucking on the other ("leeward") side. Rock masses protruding above the general surface of the region were rounded off ("sand-papered") by the fragments frozen in the base of the moving ice. Such rounded rock knobs are known as *roches moutonnées,* because from a distance they resemble a flock of sheep. Valley glaciers also produce roches moutonnées, though in much smaller numbers.

Erosion by glacier-controlled streams. Only in rare instances are the streams flowing beneath an ice sheet capable of extensively eroding the bed rock, for they are so overloaded with debris that they deposit rather than erode. However, pre-existent streams may be dammed by advancing ice, and large bodies of water may be impounded as lakes. Eventually a lake may spill over the rim of the temporary reservoir and carve a steep-walled valley across country between the outlet and a point where it is able to join an existing drainage system. With the recession of the ice most rivers return to



Figs. 75 A and B. (A) Glacier moving from right to left across bedrock floor. Scattered through ice are erratics; at lower left erratics have been plucked from leeward side of jointed bedrock face. (B) After the ice has melted. Bedrock is scratched parallel to direction of ice movement; steeper faces are on leeward side of rock hills; low places are veneered with drift. *By John Jesse Hayes.*

their old valleys. However, after the Ice Age, several rivers dammed in this manner did not revert to their former courses, as they had in the meanwhile cut their new valleys to a lower level. The Missouri River in the Dakotas and the Upper Ohio River are examples.

DEPOSITS OF CONTINENTAL GLACIERS

Naturally, the enormous amount of debris picked up during the outward movement of a continental ice sheet is deposited where the sheet recedes or disappears. Unlike the drift of valley glaciers, that left by continental glaciers is not confined to the floor of a valley, but is strewn over valley and divide alike. In the north-central United States and southern Canada, vast areas are veneered with glacial drift deposited by the last of the four great ice sheets that spread over northern North America during the recent Ice Age.

Continental glacial drift can be distinguished from other types of unconsolidated sediment by the criteria used for identification of drift dropped by valley glaciers. Ordinarily a much greater variety of rock types is represented in the drift of an ice sheet than in that of a valley glacier, or in any other type of rock mantle. This condition results from the fact that a greater area is covered by an ice sheet than is tapped by a valley glacier or even by most rivers. Rock frag-

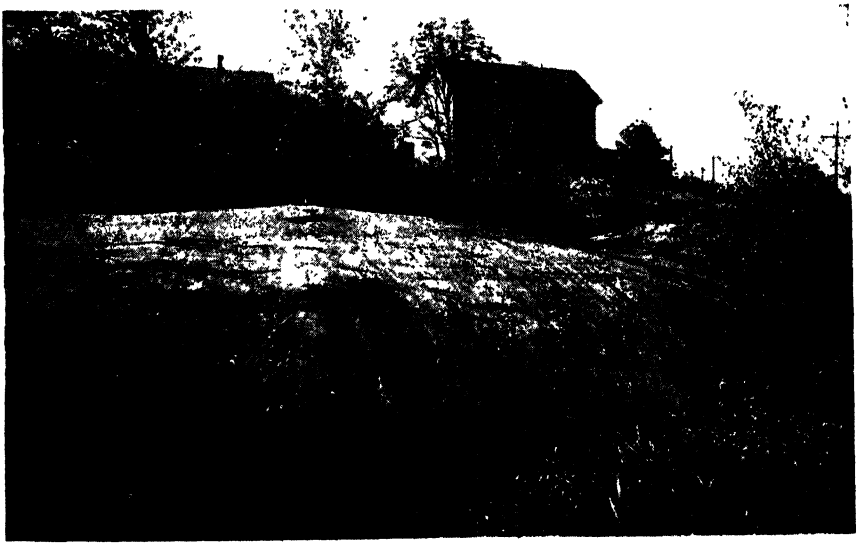


Fig. 76. A great continental ice sheet once rode over this rock, scratching and rounding it. Clinton, Massachusetts. *By W. C. Alden. Courtesy Geological Survey, U. S. Department of the Interior.*

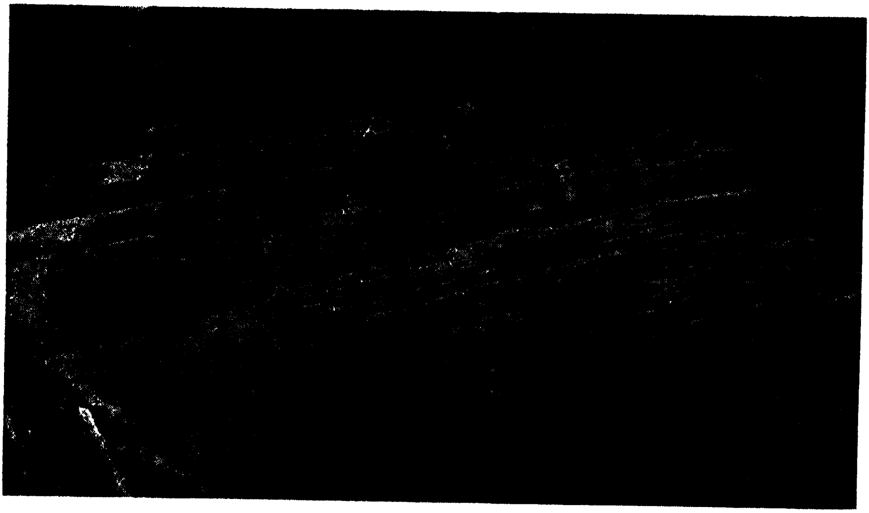


Fig. 77. Glacial grooves in dolomite. Figure standing at upper right gives scale. Yule Creek Quarry, Colorado. *By J. W. Vanderwilt. Courtesy Geological Survey, U. S. Department of the Interior.*

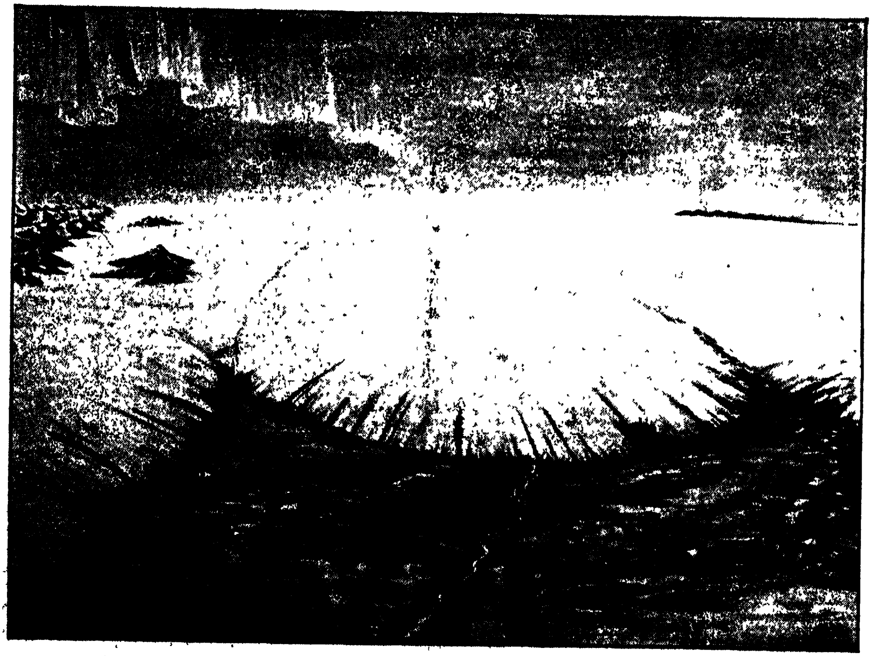


Fig. 78. Front of continental ice sheet. Terminal moraine marking maximum extent of ice lies in foreground; a recessional moraine is being built at the present position of the ice front. *By John Jesse Hayes.*

ments collected over thousands of square miles mingle together and are deposited near the margin of the glacier.

Terminal and recessional moraines. Deposition of terminal and recessional moraines by ice sheets is similar to that by valley glaciers, but there is a great difference in the length of deposits. The length of the terminal or recessional moraines of a valley glacier is limited by the sides of the valley, the terminal moraines of a continental ice sheet, in theory at least, completely encircle the ice sheet, marking the maximum extent of the ice, and measure thousands of miles in length. Actually, the margin of the ice sheet was not stationary at the same time at every place, so the terminal and recessional moraines are not continuous. The maximum advance of the last North American ice sheet is marked by a terminal moraine consisting of a series of arcs marking the position of the various lobes into which the margin of the ice sheet was divided. Parallel to these arcuate terminal moraines, and within the area covered by the maximum advance, is a series of recessional moraines which mark periods of standstill during the gradual retreat of the ice.

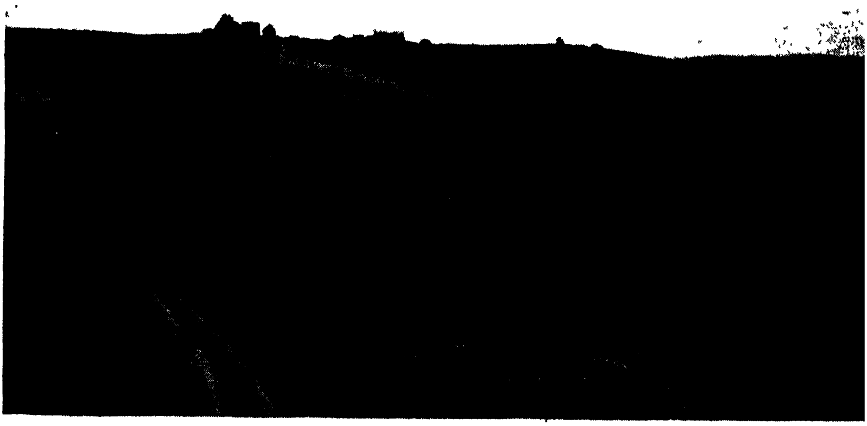


Fig. 79. Rolling topography caused by erosion of loess overlying ground moraine. Doniphan County, Kansas. ***By Oren Bingham. Courtesy Kansas Geological Survey.***

Apparently, as the ice melted, large blocks covered with morainal debris became detached from the retreating glacier. As these isolated blocks of ice melted, depressions were formed in the surface of the terminal moraine. These features, known as *kettles,* are common in glaciated regions.

Ground moraine. Melting of the continental ice sheets deposited vast acreages of ground moraine. Because this material is not confined to valley floors, where it is rather easily removed by stream erosion, ground moraine is a much more prominent feature of continental glaciation than of valley glaciation. Areas covered by ground moraine are usually gently rolling hills or plains (Fig. 79). The topography is less rugged than the terminal moraine, although they are both composed of till. In some places the ground moraine is in the form of elliptical mounds or hills, known as *drumlins* (Fig. 80). The major axis of a drumlin parallels the direction in which the ice moved, hence in any area the drumlin hills are parallel to each other. Drumlins vary in size from small mounds to large hills several miles long and hundreds of feet high. As a general rule the end of a drumlin facing the direction from which the ice came is

Fig. 80. Drumlin, deposited by ice moving from right to left. Northeast of Gleasondale, Massachusetts. ***By W. C. Alden. Courtesy Geological Survey, U. S. Department of the Interior.***

higher and steeper than the opposite end. While the evidence is unmistakable that drumlins are deposits of continental ice sheets, mechanics of their deposition has not yet been explained satisfactorily.

Large boulders transported by glaciers are called *erratics* (Fig. 81). In some instances, erratics have been deposited from the ice in strange positions, such as at the top of a knob of bed rock, creating one type of "perched" or "balanced" rocks.

Glaciofluvial deposits. An enormous amount of the material transported by continental ice sheets was deposited by streams flowing under and beyond the melting ice. This type of drift is stratified because it was sorted by current action before being deposited. Some of the debris is deposited in the channels occupied by the rivers flowing beneath the ice. On the other hand, finely pulverized rock, called "rock flour," will travel great distances, even to the sea. During the Ice Age, great quantities of this rock flour, deposited along stream courses, were picked up by the wind during periods of low water and blown over hundreds of square miles. This is thought to have been the origin of part of the Mississippi Valley dust or loess deposits.

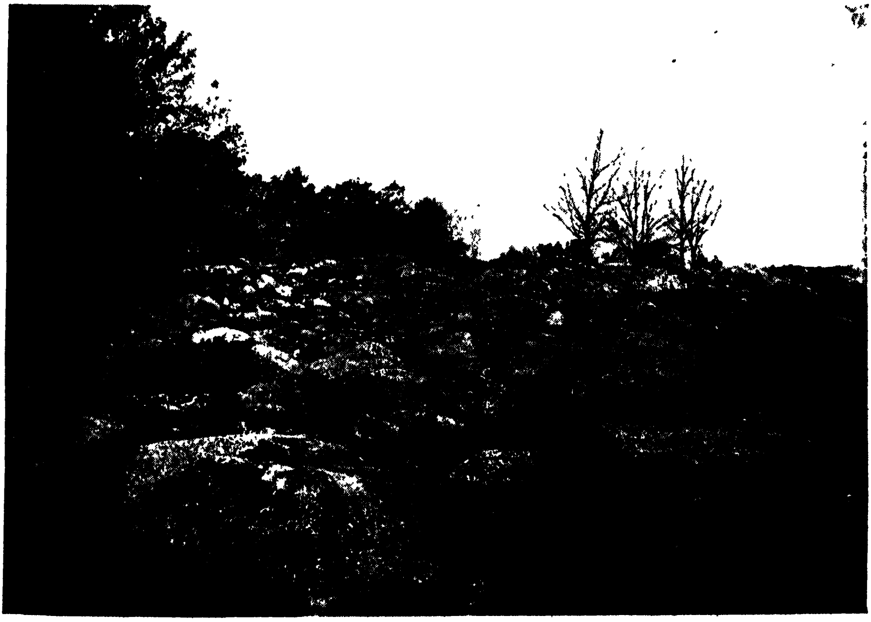


Fig. 81. Boulders or erratics deposited by a continental ice sheet near Princeton, Massachusetts. ***By W. C. Alden. Courtesy Geological Survey, U. S. Department of the Interior.***

A relatively uncommon type of glaciofluvial deposit results from "ice rafting." Icebergs, having broken off from a glacier, often carry rock fragments for considerable distances before melting causes the deposition of the load onto the floors of rivers, lakes, or seas.

Eskers. Rivers running beneath a glacier deposit sediment just as rivers do anywhere else. However, because the subglacial tunnel in which the stream runs has a flat floor and an arched roof, the deposit of sediment left in the tunnel is flat on the bottom and has an arched upper surface, the reverse of the form of a normal stream deposit. When the ice melts, this ice tunnel deposit, composed of stratified sand and gravel, makes a low, winding, elongated ridge, or *esker,* sometimes many miles or even several score of miles in length. Eskers locate the paths of subglacial drainage beneath the ice.

Kames are elliptical or dome shaped hills or irregular hummocks, less elongate than eskers, but composed of similar stratified materials. It has been suggested that they were formed by subglacial streams at the point of emergence from the ice where the tunnel widened out.

Outwash plains. The outwash plain formed by streams emerging from a continental ice sheet is comparable with the valley train formed beyond the margin of a valley glacier. Outwash plains spread out over hundreds of square miles and slope gently away from the margin of the ice sheet. Where ice has blocked preexisting drainage, temporary lakes are formed in which, due to the sudden checking of velocity, entering glacial streams build large deltas.

Moraine lakes. Because glacial deposition has been relatively recent, time has been insufficient for establishment of complete drainage, and the glaciated area is thus covered with a multitude of lakes which either occupy basins in the bed rock or depressions in the surface of the ground moraine. Where the preglacial topography was rough, the drift does not cover bed-rock ridges and hills but occupies the valleys, where it often dams streams and impounds lakes.

GLACIATION AND HUMAN ACTIVITIES

Effects upon land utilization. Both the physical appearance of a region and its utility may be greatly changed by glaciation. Erosion by ice strips off most of the soil cover, exposing broad expanses of bare rock. Such areas are to be found in Canada, where the great ice sheets of the rece[illegible] Glacial Period accumulated. Similar bare rock areas exist in some mountain valleys, where preexisting flood-plains were swept away by valley glaciers, leaving little or no soil. Extensive agricultural development is impossible where the soil cover is thin or absent.

Continental glaciation considerably modifies the preexisting topography near the outer edge of the ice sheet by the deposition of drift. If the topography was rugged, the ice wears down the bed-rock hills and fills the valleys with drift, so that the surface has less relief. On the other hand, if the ice advanced over a plain, it leaves great areas completely covered with ground moraine, and the new surface has considerably greater relief. In either case, because of deposition of the drift, the post-glacial drainage is less mature than before the ice came, and swamps and lakes are abundant.

In some areas the soil has been enriched by glaciation, because substances essential to plant growth have been brought in. In many cases, however, this gain is offset by the heterogeneity in size of the material in the drift. The great abundance of erratic boulders in New England has been a handicap to farming since the first attempts by the early colonists. Since glaciofluvial deposits are sorted, areas covered by the finer textured sediments make some of the best agricultural land in the regions covered by continental ice sheets. This is especially true of the floors of the temporary lakes which fringed the ice sheets. During the last ice age in North America a large body of water, called Lake Agassiz, was formed in what is now the Red River Valley of Minnesota, North Dakota and Manitoba. This lake was larger than any of the Great Lakes. With the retreat of the ice, most of the lake drained into Hudson Bay, but some remnants, including Lake Winnipeg, Rainy Lake, and others, still exist. The abandoned floor of this lake is one of the richest agricultural regions in North America, because of the fertility of the fine sediment which lies beneath.

Scenic and recreational areas. The regions where mountain valley glaciers exist today possess great scenic charm. For many decades people have traveled to the Alps to see the high, rugged mountains which have been sculptured by glacial ice. In the canyons are many valley glaciers and hosts of permanent snow-ice fields. The valley glaciers on Mount Rainier, an extinct volcanic cone in western Washington, have already been mentioned. The Government has set aside this mountain and some of the surrounding area as a National Park, and it is visited annually by thousands of people. Glacier National Park in Montana is so named because of the magnificent array of glacial features within its limits.

Glacier Park is an area of towering, glacier-scarred mountains, high-walled cirques, and U-shaped valleys, many of which contain long finger lakes, and a host of smaller, rock-basin lakes. Immediately to the north across the international boundary in Canada is the Waterton Lakes National Park. Farther to the northwest, but likewise along the Rocky Mountain axis, are many equally inspiring areas, such as Banff, Lake Louise, Kootenai and Yoho National Parks, and, still farther to the northwest, Jasper National Park.

An unusual by-product of continental glaciation is the Grand Coulee, with its extinct waterfall, in the eastern part of Washington (Fig. 82). Ice at one time dammed the canyon of the Columbia River, so that it had to cut across a lava plateau for many miles before it could rejoin its old channel. During the relatively short time that the

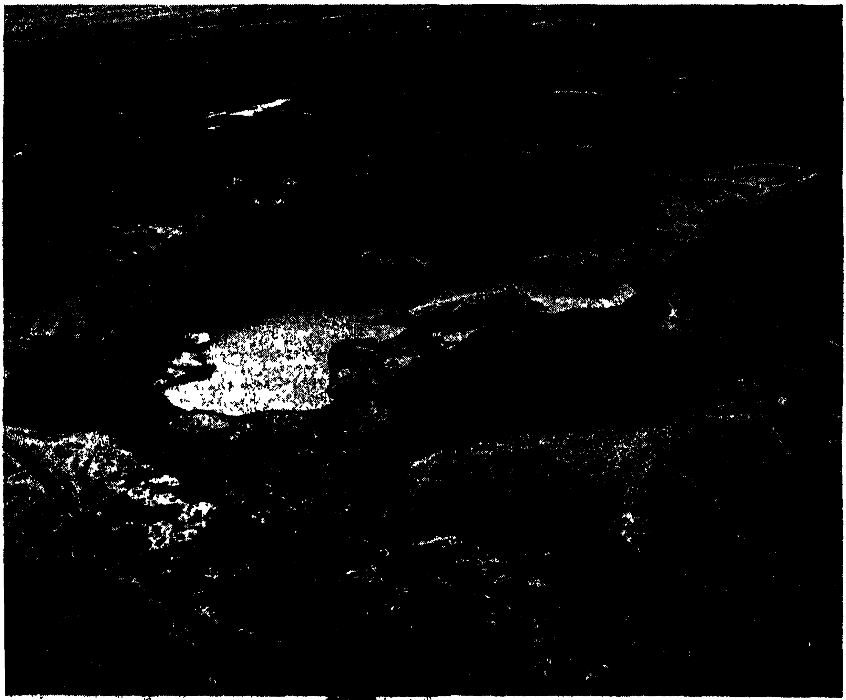


Fig. 82. Close-up of Dry [illegible] in Grand Coulee, Washington. At upper left is valley floor at higher ley[illegible] the Columbia River once plunged over the brink in a twin horseshoe fal[illegible] mightier than Niagara. *By permission Spence Air Photos.*

river followed this temporary channel, it cut a deep canyon at the head of which was a precipice several hundred feet high. Over this, the river tumbled in a fall far greater than Niagara. Later the ice dam melted away and the river reverted to its old channel.

The creation of lakes through glacial activity has been mentioned in many places in this chapter. Some of them are widely used for fishing, hunting, boating, and swimming. Parts of Ontario and Quebec contain hundreds of lakes in depressions in the bed-rock surface scoured out by one of the continental ice sheets. Erosion of preglacial valleys helped to create the Finger Lakes in New York and Lake Chelan in Washington. Erosion by valley glaciers has produced many small but beautiful cirque lakes. Scouring, combined with damming by morainal deposits, made beautiful Lake Louise in the Canadian Rockies near Banff, many of the famous lakes in the Alps, and thousands of lakes in other mountainous areas. Even the Great Lakes were evolved by a combination of scouring, drift-damming, and warping of the earth's crust.

Economic products. The quantity of sand and gravel produced annually from glacial drift in the United States is enor-

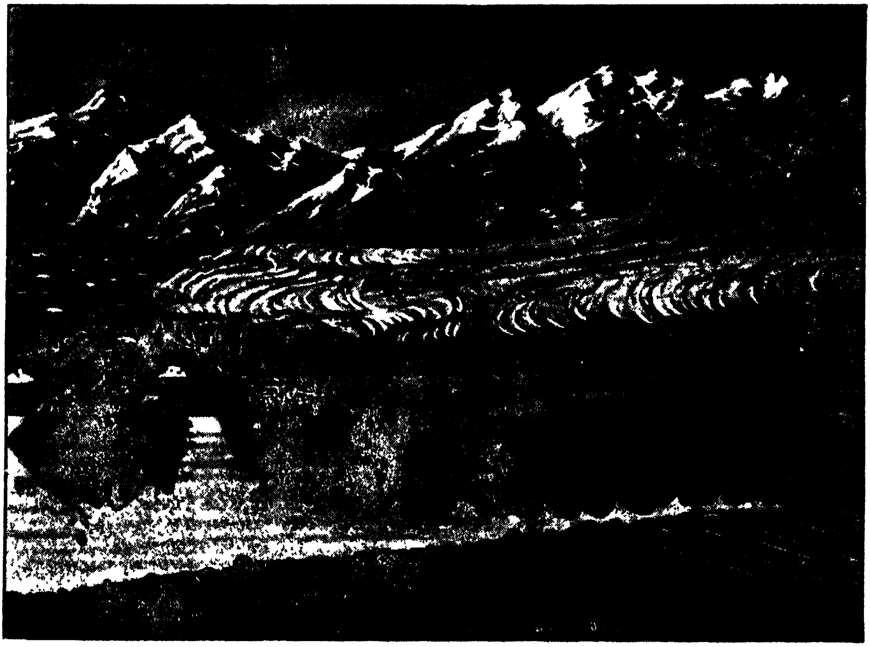


Fig. 83. Valley glaciers which reach the sea are the sources of icebergs that imperil shipping. ***By John Jesse Hayes.***

mous. These materials cannot be economically exploited in unsorted till, but they are obtainable from well sorted glaciofluvial deposits. The largest sand and gravel deposits occur where glacial streams built deltas in temporary lakes around the margin of the ice sheet. Glacial sand and gravel deposits are also found in mountain valleys, where streams drained valley glaciers.

Many farms and small communities obtain their water supplies from ground water stored in glacial drift. Most drift is permeable and, where thick, is capable of storing a vast amount of water. Because of the insoluble character of the minerals ordinarily occurring in glacial deposits, the water is commonly soft, and in that respect is superior to the average bed-rock ground water.

Icebergs. Many glaciers in high latitudes (Greenland, Labrador, Alaska) reach the sea where huge masses of ice break off along crevasses and tumble into the water (Fig. 83). Icebergs are not important geological agents, but are a very serious menace to navigation. Ever since the steamer Titanic crashed into a berg and sank with a loss of 1,513 lives in 1912, the United States Coast Guard (with the financial assistance of other nations) has patrolled the North Atlantic during the months when icebergs are liable to drift across the steamship lanes. When a berg is sighted, all nearby shipping is warned of its position from time to time until it melts.

CHAPTER 7

Direct Action of Gravity

GRAVITY IS THE FORCE THAT MOVES MATter toward the center of the earth, or toward the center of other cosmic bodies. Since earliest time, gravity has been a dominant factor in the geologic processes operating on and within the earth. The downward movement of rain and snow is due to gravity. Water running on the earth's surface, always seeking a lower elevation, owes its movement to gravity. The slower movement of underground water is due to the same force.

Gravity also causes the downward settling of windblown material and the deposition of sediment in the channels of streams and on the floors of lakes, seas, and oceans. Lava erupted from a volcano flows downgrade until the congealing of the liquid rock prevents further movement. Likewise, glacial ice moves because of the force of gravity.

It is believed that gravity also operates on a much grander scale within the earth's crust, causing lighter segments, such as the continental masses, to stand at higher elevation than the denser ocean covered segments. Similarly, the loading of the surface at any one place, as in large river deltas, causes a slow sinking of the underlying crustal segment, which will be compensated by an uplift elsewhere. This gravitative adjustment of the earth's crust is known as *isostasy*.

From these examples, it is evident that gravity is the fundamental force in the operation of most geologic processes. Its work is done mainly through such agents as water and ice, and its results are described in other chapters. This chapter is concerned with three types of deposits and land forms that are produced largely by gravity. They are (1) land forms resulting from subsidence of the surface, (2) those formed by the accumulation of fallen material, and (3) those formed by mass movements of rock in a direction principally downward but with a considerable horizontal component, such as landslides. Even in these movements, other geologic agents, especially ground water, participate.

SUBSIDENCE

Subsidence is the downward movement of earth material lying at or near the surface. It is essentially vertical motion with little or no horizontal component.

Causes of subsidence. The primary force producing subsidence is gravity. But before gravity can act, other agents must operate so as to create space into which the earth materials can sink. Both natural and human agencies can create conditions that will cause subsidence; the immediate cause may be either the actual removal of earth materials from beneath the surface or the compaction of the underlying rock. In the former case subsidence at the surface will follow the failure and collapse of the roof above the void zone.

The formation of caves by solution of minerals of soluble rocks by ground waters was described in Chapter 4. Rocks especially susceptible to removal in this manner are limestone, gypsum, and salt. The burning of combustible material, such as peat and coal, will likewise reduce the volume of rock beneath the surface. Openings in morainal deposits are formed through the melting of isolated blocks of glacial ice.

Slumping may also result from the mechanical removal of earth materials. Occasionally, an underground stream has sufficient velocity to erode physically the rock in its channel, thereby creating both a tunnel and a zone of weakness along which collapse may take place. Lava tunnels, formed by the draining off of still-liquid lava from the core of a flow after the top and sides have congealed, are also areas of potential subsidence. In parts of New Mexico, depressions formed by the collapse of such lava tunnels contain small lakes.

The weight of the overlying material may cause outflow of beds of quicksand or plastic clay, which will be accompanied by settling of the higher rock.

Examples are numerous of subsidence of the surface in regions where mining activity has removed large quantities of rock such as coal and ore. Certain coal mining towns have had to be abandoned, because of slumping into the abandoned workings beneath. The removal of salt and sulphur by means of wells creates a cavernous condition underground and so may result in subsidence of the surface.

The production of oil from a pool on the Gulf Coast of Texas was accompanied by subsidence, but this was an exceptional case.

Compaction of rock is caused in several ways, such as overloading of the surface, or removal of water by evaporation or by drainage from the underlying soil and rock. Drainage of the English fenlands resulted in sufficient compaction to have lowered the surface 13 feet since 1848.

Results of subsidence. The principal land form resulting from subsidence is a *sink* (Fig. 84). Generally these are undrained depressions, containing pools or lakes where they are deep enough to intersect the water table. If sinking is due to failure of roofs of caves, the shape of the depression is approximately that of the collapsed area. Therefore limestone sinks tend to be very irregular because of the ramifying nature of the underlying caverns. Characteristic features of recently formed sinks are steep, often nearly vertical walls. The break at the edge or rim of a sink is abrupt. Some parts of Florida and Kentucky contain such an abundance of sinks

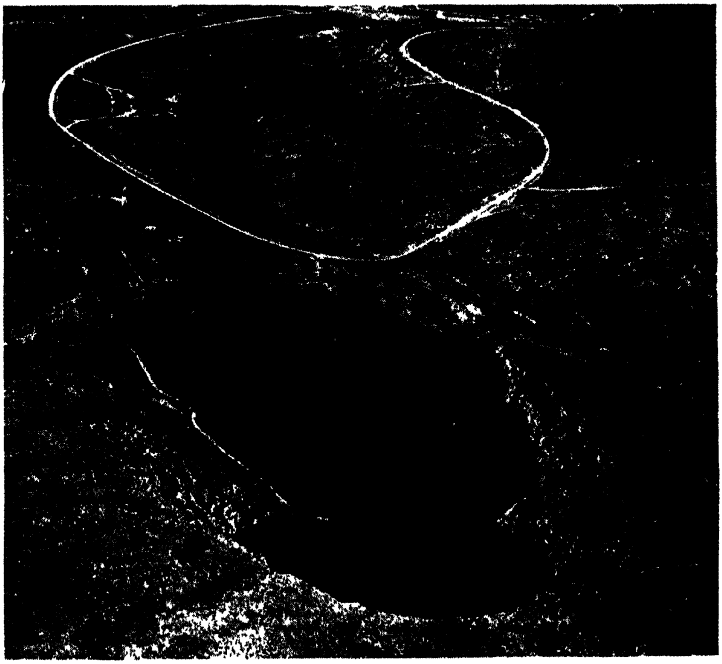


Fig. 84. Two deep water-filled sinks 16 miles east of Roswell, New Mexico. *By permission Spence Air Photos.*

that the land cannot be cultivated and even communication is difficult. A sink-dominated region is spoken of as possessing a *karst* topography, because it is strikingly developed in the Karst region on the eastern shore of the Adriatic Sea. Fortunately for land utilization, by no means all limestone regions exhibit such topography. In many regions either the limestones have resisted large scale solution by underground waters, or the roofs above the caves have been sufficiently competent to withstand the downward pull of gravity.

Kettle holes, which are formed in moraines due to slumping ac-

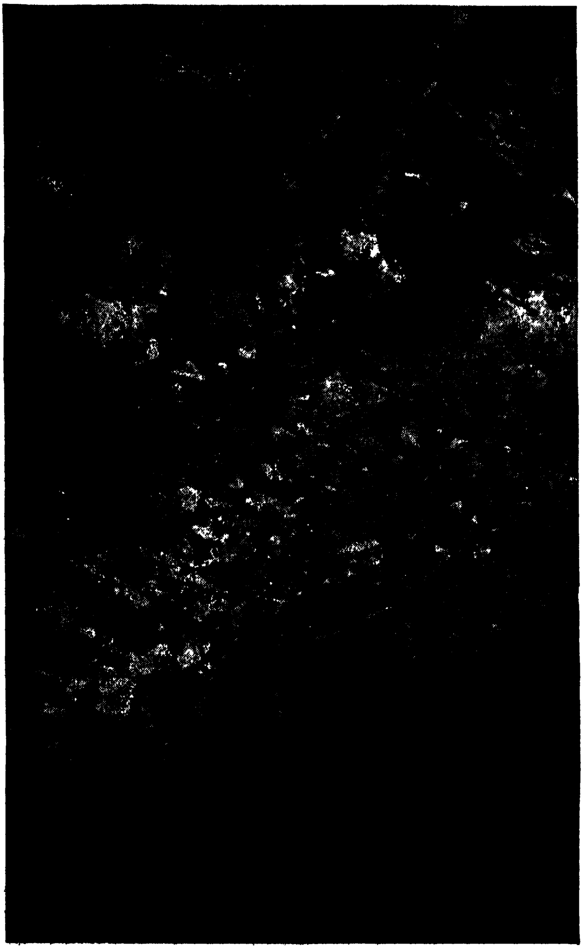


Fig. 85. Breccia composed of unsorted but cemented angular rock fragments and caused by collapse into a large cavern. Mackinac Island, Michigan. *By Kenneth K. Landes.*

companying the melting of ice, are described in the preceding chapter (p. 158).

Subsidence resulting from the activities of man have, of course, taken place in historic time. Also, sinkings due to collapse of the roof overlying natural caverns have been witnessed, although by far the greater number of these are prehistoric. An acre of land in western Pawnee County, Kansas, sank in 1898, and took with it a railroad station.

Another land form which results from a combination of ground water activity and subsidence is the natural bridge. The famous bridge near Lexington, Virginia, is all that is left of the roof above a cavern dissolved from limestone. The cave was elongate, and through it flowed an underground river. Subsidence of most of the roof exposed the stream; that part which has not yet collapsed bridges the valley in which the stream runs. A cave in a gypsum bed in Barber County, Kansas, has also produced a natural bridge because of caving of its roof until only one small segment remains.

Collapse breccia. Where sinking due to the collapse of cavern roofs has taken place recently, the observable result is a topographic feature. But beneath the floor of the sink the rocks are unquestionably in a disturbed condition. The highest rocks in the collapsed zone may have dropped without extensive shattering. But below these, and especially within the space which was once a cave, the rock is a rubble consisting of angular fragments of varying size and orientation. Ground water, circulating through this porous mass, tends to cement the fragments into a coherent rock known as *breccia* (Fig. 85).

Such collapse breccias have been exposed by the forces of erosion, especially in the vicinity of Mackinac Straits, which lie between the Northern and Southern peninsulas of Michigan. In fairly early geologic time, the area was the rim of a rock basin which contained thick beds of salt among the rock layers. Ground waters reached the salt from beneath the rim of the basin, creating enormous caves. When the cave roofs could no longer support the overlying rock, collapse took place. Sometimes the break was relatively local, and rock fragments from the overlying rock tumbled downward until a rubble-filled chimney extended from the floor of the original cave upward through several hundreds of feet of rock to the surface. When this collapse debris became cemented into breccia, a rock resulted which was more resistant to erosion than the surrounding rock. Consequently, the Straits area today contains a number of prominent "pillar rocks" which contribute much to the picturesque beauty of the region.

By no means all of the collapse in the Mackinac Straits area was local, however. Less prominent, because it does not produce pillar rocks, but more common was collapse over wide areas of cavern roof. This resulted in the dropping of great blocks of sedimentary rock. Inevitably, during the dropping the blocks were tilted. It is by their dips of 6° to 25° that the blocks can be recognized as out of place. Also, some blocks dropped farther than others, so that younger rocks may be on the same level as nearby rocks of much greater geologic age.

ACCUMULATION OF FALLEN MATERIAL

Wherever slopes are steep, rock material loosened by weathering or other processes will fall, roll, or slide to the foot of the slope. In mountainous regions the debris is so plentiful that distinctive topographic features are produced. Huge piles of angular rock fragments accumulate at the foot of cliffs as a cone which rises to an apex far up the slope. The mountain dweller calls this debris "slide rock"; the geologist refers to it as *talus* (pronounced *tail-us)* (Fig. 86). Talus cones are common features in rugged regions, especially above the timber line. Although apparently standing at the "slope of repose," most talus piles are slowly creeping downward and outward.

Accumulation of loose material solely through the action of gravity is universal, but rarely, except in mountainous regions, are these features of any great quantitative importance.

MASS MOVEMENTS

Mass movements differ from subsidence in the direction of movement. Both are due to gravitative attraction, but the movements described below are not only downward but also lateral. In fact, the horizontal distance traveled by the debris is considerably greater than the vertical in most cases. Mass movements are of three main types: creep, rapid flowage, and landslides. Creep and rapid flowage differ from landslides in the character of the movement and not in the velocity, as landslides may be very slow or they may be rapid and catastrophic. Sliding involves the movement of a mass along a definite plane, whereas flowage takes place through continuous deformation, with no definite plane along which slippage occurs. The greatest movement in the case of flowage is at the top of the flow, with

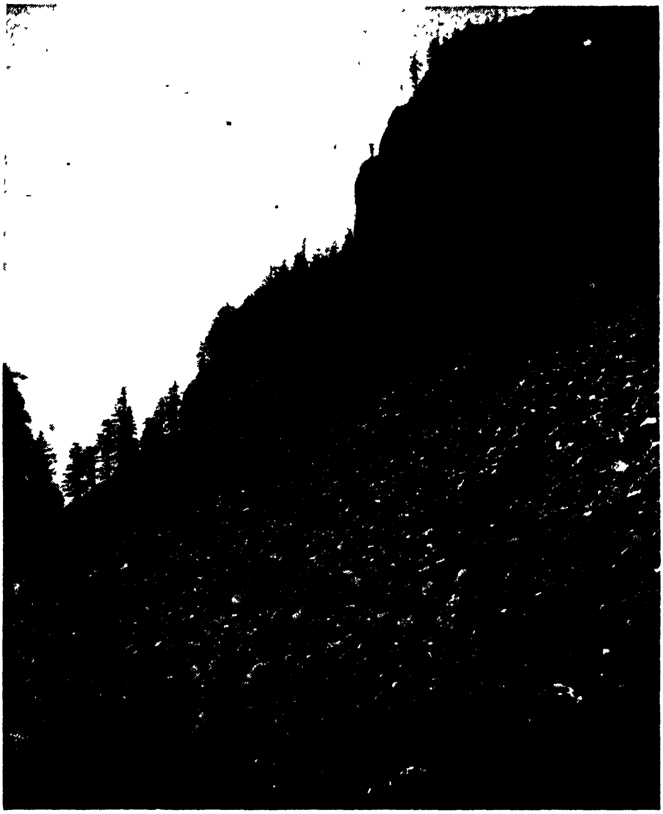


Fig. 86. Talus or "slide-rock" resulting from fall and accumulation of rock fragments from cliff at upper right. Cape Horn, Columbia River. *By Arthur M. Prentiss.*

none at the bottom, whereas in a landslide, the entire block moves at approximately the same rate.

The force producing mass movement is gravity, but there are many contributing factors, both natural and human.

Creep. The downward creep of soil, talus accumulations, and rock (Fig. 87) has been termed slow flowage in contrast with rapid flowage. Movement is so slow as to be imperceptible except by means of observations taken over a long period of time. Because of the low velocity, some forms of creep have been referred to as rock glaciers.

Conditions favorable to creep are the existence of unconsolidated materials, or bed rock either laminated or broken by closely spaced joints, by faults, or by other planes of separation. The actual downslope movement may be effected by (1) wedging or prying through plant and animal activity, (2) expansion of water freezing in cracks in the soil, (3) undercutting by rain wash and streams, (4) increase in load due to rain or snow, and (5) a disturbance in equilibrium caused by earthquakes or animals (including man).

Creep can be recognized by several criteria. Where the creeping mass is forested, many trees have curved trunks, because, when young, they were tilted downslope by movement of the rock mantle; during later growth the trunk has been erect. Fence posts, telegraph poles, retaining walls, and foundations are tilted downslope by similar movement of the rock mantle. Roads and railroads may be moved out of alignment.

Rock glaciers generally can be recognized by their slope, topographic position, and composition. They are typically glacier-like tongues of coarse angular rock fragments furrowed in the direction of movement by a series of parallel ridges, and heading in a steep-

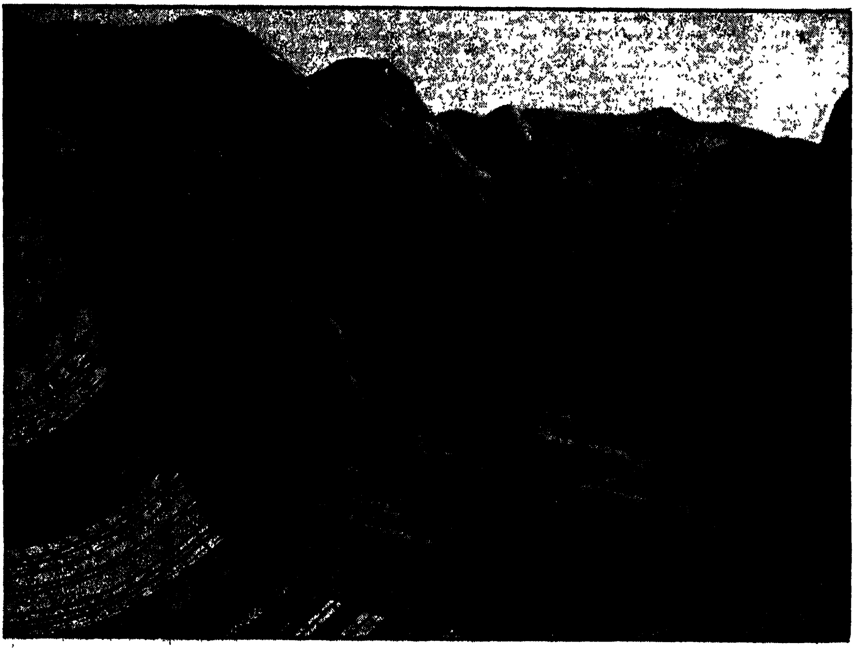


Fig. 87. Soil creep, a form of slow flowage. Rock and soil mantle is slowly moving toward lowest part of valley where river flows. Bend in tree trunks is characteristic. *By John Jesse Hayes.*

walled amphitheater, comparable to the cirque of a true glacier (Fig. 88). The waste composing a rock glacier is derived from the cliffs at its head.

Rock glaciers were first recognized in the Nizina district, Kennicott Valley, Alaska, where over 30 exist. A description of one follows:

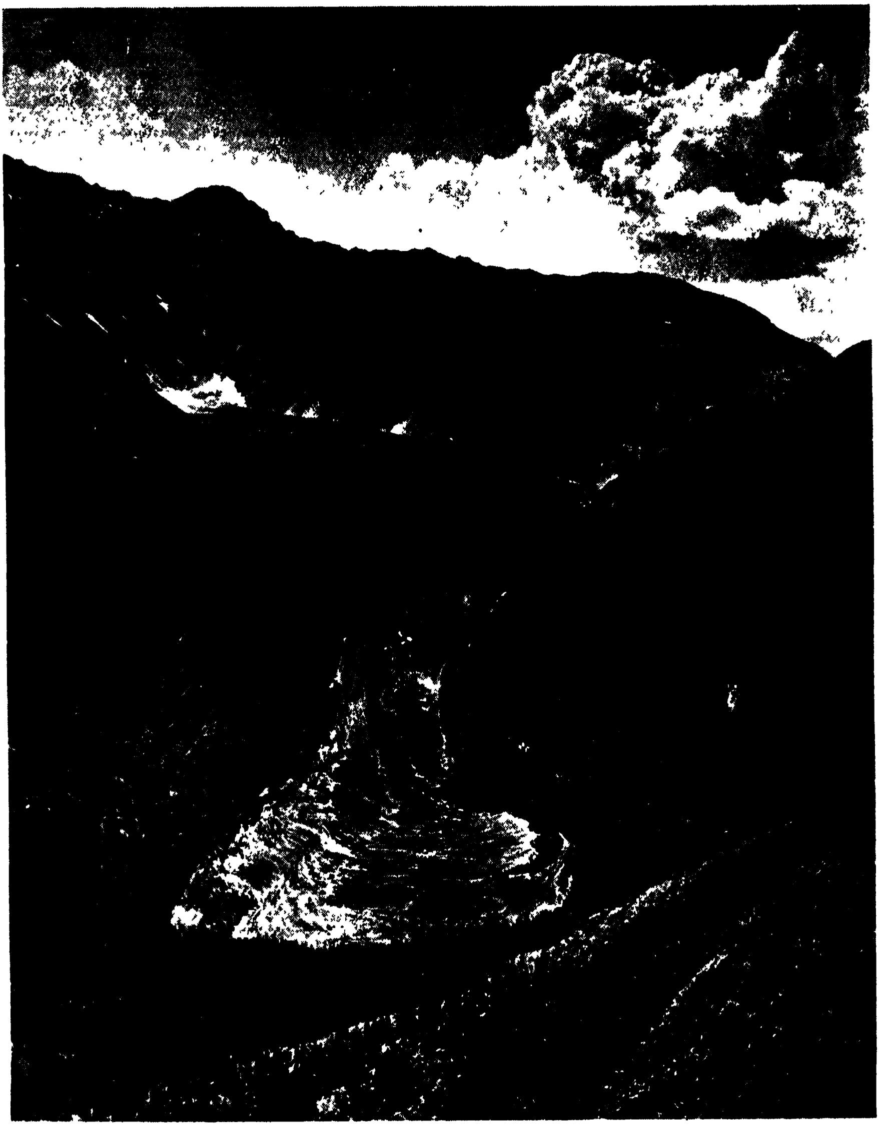


Fig. 88. Rock glacier, McCarthy Creek, Alaska. *By F. H. Moffit. Courtesy Geological Survey, U. S. Department of the Interior.*

> The rock glacier heads in the talus cones which have formed at the base of the steep rock cliffs. These cones have nowhere grown to large size, the materials evidently having moved on down valley as parts of a rock glacier as fast as they were supplied from above. From the base of the more vigorous talus cones, smooth, ridgelike lines extend on down the rock glacier, seeming to show that the forward movement has been uniform and continuous. Longitudinal ridges mark the surface for the upper three-fourths of the total length of the flow. The cirque basin is a hanging valley extending down to an elevation of about 4,000 feet, below which it joins the broad V-shaped valley of the McCarthy Creek. As it passes over the lip of this hanging cirque the rock glacier cascades steeply down the valley side, and upon reaching the gentler slope below, being no longer confined by restricting valley walls, it spreads out in a great lobe along the valley bottom. In this lower lobe the longitudinal surface markings disappear and give place to a set of concentric ridges or wrinkles. The origin of these wrinkles is not clear, but they strongly suggest rings of growth, and may represent the amount of annual movement of the rock glacier. At its foot the flow has pushed across the valley bottom almost to the base of the east valley wall.[1]

Rapid flowage. Earth flows, mud flows, and debris avalanches are examples of rapid flowage. This type of mass movement differs from slow flowage only in the velocity of the movement. In all cases the flowage is sufficiently rapid to be noticeable, and it may be swift, and even catastrophic if human habitations lie in the path of the flow. The reason for the greater velocity is the presence of a larger amount of water penetrating the soil or rock. Water acts as a lubricant by decreasing friction; therefore, the more water present, the greater the speed of the flow. It also adds to the weight of the mass since it replaces air in the open spaces between the fragments.

The combination of conditions most favorable for rapid flowage is the presence on steep slopes of unconsolidated or poorly consolidated materials which become water-soaked through abnormal precipitation. The "angle of repose" for wet material is much less than for the same material when dry; therefore, dry soil or loosely consolidated rock standing at the angle of repose for dry material is no longer in equilibrium when it becomes watered.

The great Slumgullion mud flow, in the San Juan mountains of Colorado, advanced for more than six miles and finally dammed a fork of the Gunnison River, creating Lake San Cristobal. The flow started in weathered and water-soaked volcanic rocks high in the mountains and flowed down the steep valley of a tributary of the Gunnison River.

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[1] Capps, Stephen R., Jr., "Rock Glaciers in Alaska," *Journal of Geology*, 18, 1910, pp. 367-368.

Clayey soils on the sides of valleys, when sufficiently saturated with water, frequently start to flow and form a narrow opening in the river bank through which a large volume of material will flow. Many such earth flows have occurred in the St. Lawrence Valley, where glacial clays underlie terraces along the river and its tributaries. A typical flow on the Riviere Blanche in Quebec has been described as follows:

> The sloping river bank twenty-five to thirty-five feet in height gave way suddenly and allowed the saturated clay and overlying sand of the cultivated terrace lands to rush forward through a 200-foot gap. Although little or no water was visible, movement of the mass was rapid and big blocks of the relatively dry upper clay and sand floated on the flowing substratum "like steamers on a river." An area of the terrace some 1,700 by 3,000 feet with a volume estimated at almost 3,500,000 cubic yards passed out through the bottleneck in three or four hours, leaving a depression fifteen to thirty feet deep at the upper end and sloping downward only twenty or twenty-five feet to the outlet. The material removed filled the Riviere Blanche valley for two miles, damming it to a depth of fully twenty-five feet.[2]

Large "clayslides" of similar type in Norway are not infrequent; one such flow killed 112 people. Mud flows in the Alps Mountains have likewise overwhelmed and demolished villages.

A debris avalanche is a flowing slide of soil, mud, or rock down steep slopes in humid climates. Abnormally heavy rains increase the weight of the mantle rock and at the same time lubricate the mass so that it starts to slide. The initial movement is slippage, but when gentler slopes are reached the mass ceases slipping and starts to flow. This type is therefore transitional between mass movements entirely by flowage and those which consist wholly of sliding action.

Rapid flowage leaves marks by which it can be recognized long afterwards. The surface at the head (upper end) of the flow shows signs of slumping, with backward tilted (slope opposite to that of the hillside) slump blocks. Where a large quantity of material is moved, the upper end of the flow track is a valley-like depression. The clay earthflows of the St. Lawrence Valley produced depressions

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[2] Sharpe, C. F. Stewart. *Landslides and Related Phenomena,* pp. 51-52. New York: Columbia University Press, 1938.

15 to 30 feet deep in terraces along the valley. The lower end, or toe, of a flow is a bulging, fissured, domelike mass of debris whose texture depends upon the type of material involved. Flows down steep slopes have a narrow track and leave a very distinct scar on the hillside.

Landslides. Contrary to popular conception, a landslide is not necessarily rapid. It may be as slow as soil creep, or it may be swift and destructive. Landslides differ from flows in the mechanics of movement; the moving material slides upon a definite slippage plane beneath which the rock remains stationary. Classified in this group are slumps, slides, and falls of soil and rock.

The causes of landslides can be separated into (1) the environmental conditions favoring sliding and (2) the supplementary conditions which initiate sliding. The former group includes the presence of (a) weak rocks, (b) relatively steep inclinations of strata approximately parallel to the slope of the surface, (c) abundant fractures, and (d) steep slopes or even cliffs. Some of the initiating causes are the removal of support either through natural erosion or engineering activities; overloading by natural or human agencies; reduction of friction because of increased water content at times of heavy abnormal precipitation or other cause; prying or wedging by freezing of water; the growth of tree roots in fissures; and earth vibrations resulting from earthquakes, blasting, or the passage of heavy vehicles.

Landslides are fairly common phenomena and occur on a small scale nearly everywhere. Large slides are less numerous. Most occur in sparsely settled areas, but disastrous slides are by no means unknown. Examples of different types of slides are given below.

An exceptionally slow-moving landslide at Point Firmin on the California coast was observed during 1939 and 1940 (Fig. 89). Shales and sandstones with a seaward inclination of 10 to 15 degrees were involved. Lubrication of shale by ground water caused a rock mass a third of a mile across to move slowly down the slope of the stratification toward and finally into the ocean. The wetting of the shale was perhaps increased by irrigation which permitted a greater volume of water to enter the underground water circulation than had been the case before. In a little over a year this block moved about eight feet seaward, and a fissure developed at the landward end of the slide.

The newspapers of the country carried daily accounts of the slow sliding of a rock mass down the side of Carbon Mountain near

Durango, Colorado, in December, 1932. The mass involved was about 1,800 feet long, 600 feet wide, and 100 feet deep. It moved through a total distance of about 700 feet. The maximum recorded rate was 45 feet per day.

Many landslides are started by earthquakes. An outstanding example is the series of slides that occurred after an earthquake in December, 1920, in the loess deposits of the province of Kansu in the interior of China. About 100,000 lives were lost by engulfment in great masses of earth that slid off the hills into the valleys. Many villages were completely buried. A sudden slide of mud, rock and debris, probably likewise started by an earthquake, buried several dwellings including an apartment house in the town of Juneau, Alaska, in November, 1936. A number of people were killed. One man buried up to his neck in the slide rock was rescued. A slide of great magnitude in the Himalayan region was caused by solution:

> Sir William Conway describes the matter of a little shifting of rock which caused the formation of Gohna Lake, in the Central Himalayas, where the spur of a large mountain mass pitched bodily into the valley below. The front of the mountain had been undermined

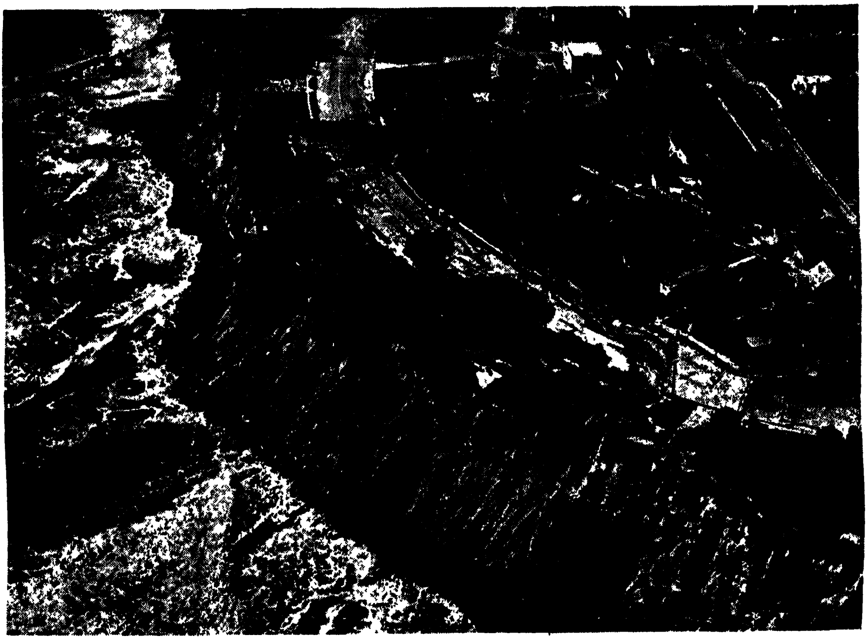

Fig. 89. Slow-moving landslide caught in the act. Point Firmin, near Los Angeles, California. *By permission Spence Air Photos.*

> by springs until there was no longer sufficient support, and in the twinkling of an eye a large part of the mountain slid down and shot across the valley, damming its river with a lofty and impervious wall. *Masses of rock were hurled a mile away, blocks of limestone weighing 30 to 50 tons being sent through the air like huge cannon shots. It is estimated that this slide carried with it 800,000,000 tons of rock and debris.*[3]

Landslides produce a characteristic topography. For many years after the slide takes place a very definite "scar" is discernible on the valley wall whence the material came. The slide rock itself can be recognized by the reversal of surface slope, which creates a saddle between the highest point on the block and the "scarred" hillside. The saddle is hummocky and is quite distinct from any topography resulting through erosion by running water.

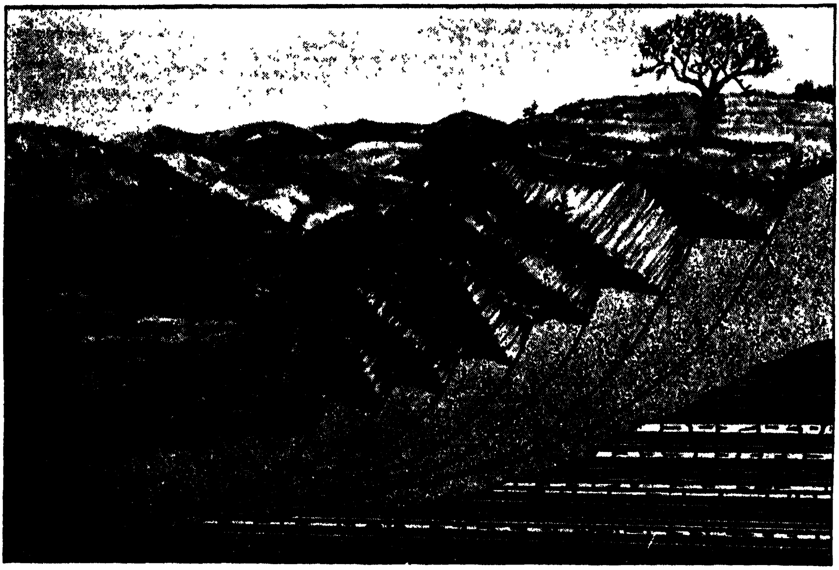

Fig. 90. How landslide terraces are formed. Multiple landsliding. *By John Jesse Hayes.*

Slides of the slump type which have not moved out from the point of origin far enough to leave a scar can be recognized by the presence of slumped blocks arranged in a series of steps or small terraces (Fig. 90). The "risers" of the steps are steeply inclined or vertical slippage planes; the surface of the step or slump block in most cases inclines gently toward the riser of the next higher step.

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[3] Mitchell, Guy Elliott. "Landslides and Rock Avalanches," *National Geographic Magazine,* Vol. 21, No. 4, April, 1910, p. 276.

Most landslides come to rest on a valley floor and in many instances dam the stream flowing through the valley, forming a lake. Such lakes are temporary because the water flowing over the dam soon cuts through the unconsolidated material and drains the lake. The Gros Ventre River south of Yellowstone Park was dammed by a slow-moving landslide in 1908, and a small lake was formed. part of which still exists. In 1925 another slide took place downstream from the first and formed another lake. This landslide, locally known as the "Kelly Slide," was a fast-moving slide. Numerous lakes in the Alps and Pyrenees mountain ranges are due to landslide dams.

Landslides and other types of mass movement present a serious problem to the engineer. Not only may such movements be destructive to railways, highways, canals, and habitations already in existence, but they may also cause a great deal of trouble during work on engineering projects. The sliding away of a large segment of the great earthen dam at Fort Peck, Montana, before construction was completed, is an example.

Several methods have been employed to combat mass movement. One, which has been used with considerable degree of success in stopping slow-moving masses, involves the driving of drainage tunnels into the sliding mass, thus lessening the quantity of water and thereby reducing lubrication of the rock. In at least one instance, the slippage planes have been dried out by hot air forced into the clay through drill holes. Still another method is to drill a series of deep vertical holes in a line across the sliding or creeping material and fill them with concrete.

Avalanches. An avalanche is a mass of snow and ice, with attached soil and debris, which hurtles down the side of a mountain with great velocity. Large accumulations of snow will soon compact into a dense mixture of ice and snow. When a thaw permits water to accumulate on the under side of such a mass, perched high on a mountain flank, the "skids are greased," so that the mass may suddenly break away and rush down the mountain side. Avalanches are fearful agents of destruction, for they snap off large trees and overwhelm everything else in their path until they come to rest at the foot of the slope. The air in front of an avalanche may be compressed to such an extent that trees beyond the path covered by the slide are uprooted by the wind. The forest clad mountains of the West and Alaska have been gashed in many places by mighty avalanches. In the early years of the current century, an avalanche in the Cascade Mountains of Washington caught a train crossing its path, completely demolished it, and killed many of the passengers.

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CHAPTER 8

Oceans and Lakes

All of the water on the earth's surface, together with that in open spaces below the surface, constitutes the *hydrosphere.* The work of running water and ground water has been discussed; the present chapter is concerned with the activities of lakes and oceans. One feature common to both lakes and oceans is that their surfaces are horizontal. Because the oceans are interconnecting, their upper surface over the world makes a curved plane referred to as *sea level.*

The oceans and, to a relatively minor extent, the lakes are agents of erosion and deposition. These processes are most active adjacent to the shore line; therefore, the resultant land forms are confined to the shores of lakes and oceans. Of much greater geologic importance is the function of lakes and oceans as basins of deposition of sediment brought in by streams and other agents and for sediment generated by the waters themselves. Some lakes, especially in the geologic past, have also been basins for the precipitation of chemical compounds, such as salt. The sediment deposited in a lake has an uncertain future, for in most cases the lake bottom is but a temporary resting place. If the lake stands above base level, it will eventually be destroyed and its sediments will resume their seaward journey through transportation by running water. Although most of the sediment carried to the ocean is deposited fairly close to shore, it has a much more permanent status.

In addition to the role played by lakes and oceans in geology, these bodies of water are of great importance to mankind. During historic time they have acted as protection from invasion or as pathways to invasion. For many centuries oceans, especially, have provided means for the cheap transportation of both people and goods. By far the greater part of world commerce is carried on by water transportation. With certain exceptions, such as the Great Lakes on the North American continent, lakes are not important as arteries of commerce, but lakes have some uses for mankind which the oceans do not possess. Most lakes contain fresh water, and many are utilized as water supplies for domestic, municipal, and industrial use. These natural reservoirs also act as a deterrent to floods, affording storage for abnormally high runoff in their drainage basins. Lakes and oceans yield a variety of economic products which large numbers of people are employed in obtaining. Some coastal districts, such as parts of New England and the Maritime Provinces of eastern Canada, have important fisheries. Other economic products are shellfish, sponges, and even pearls. Salt is obtained through the evaporation of both ocean water and the water of interior salt lakes. Lakes and oceans afford recreation in swimming, boating, and fishing; hence, beach resorts are an important phase of our life and activities.

Oceans and, to a lesser extent, large lakes affect the climate of nearby land areas, especially where the prevailing winds are onshore. The prevailing winds are westerly; the climate on the west coasts of the continents is ocean-controlled to a considerable extent. Since large bodies of water do not pass through as great an annual temperature range as do land areas, the winds off such waters are relatively warm in winter and cool in summer, lessening the annual temperature variation on the nearby shores. In addition, great currents, such as the Japanese Current in the north Pacific and the Gulf Stream in the north Atlantic, are constantly bringing equatorial waters northward while cold currents, like the Kamchatka and Labrador currents are shifting sub-arctic waters to the south, thereby furthering this temperature equalization process. Warm winds passing over large bodies of water pick up much moisture which is later dropped on the coastal lands. The northern shores of western North America and of western Europe are well-watered and have mild winters and cool summers because of the combination of westerly winds and oceanic currents. The annual rainfall and the winter snows are greater on the west side of the southern peninsula of Michigan, facing Lake Michigan, than they are on the eastern (Lake Huron) side, because the prevailing westerlies pass across Lake Michigan and then drop the greater part of their recently acquired moisture on the first land areas reached.

OCEANS

Distribution. The waters of the oceans cover three-fourths of the earth's surface. If all this water were drained away, the continents would stand as plateaus high above the oceanic floors. Parts of the *continental platforms* lie below present sea level; the fraction of the earth's surface floored by continents is actually one-third instead of one-fourth. Those parts of the continental platforms that extend out beneath the sea to depths of about 600 feet are known as *continental shelves* and the overlapping waters are referred to as *marginal* or *epicontinental seas.* The eastern border of the North American continent is a continental shelf extending out beneath the waters of the Atlantic for an average distance of about 100 miles. The continental shelf on the Pacific side, however, is very narrow, and in places the edge of the continental platform practically coincides with the shore line. The slopes connecting the continental platforms with the ocean basins are known as *continental slopes.* Since, as a general rule, the gradient of the slopes is a gentle one, the fringe zone between the platforms and the basins is many miles in width. The ocean basins are major depressions in the earth's surface. It is believed that they have been in existence throughout traceable geologic history.

Depths. The average depth of the ocean is approximately two and one-half miles. This is about five times greater than the average elevation of the continents. Consequently, the volume of water in the ocean is much greater than the volume of land above sea level. The deepest ocean is the Pacific, which reaches a maximum depth of about six and one-half miles just east of the Philippines.

Composition. Between three and four per cent, by weight, of the ocean water is mineral matter in solution, of which about seventy-five per cent is common salt (sodium chloride). Other important salts are magnesium chloride and the sulphates of magnesium, calcium, and potassium. About one-third of one per cent is calcium carbonate. Most geologists believe that the oceans were originally fresh and that the principal source of the acquired mineral matter is the land above sea level from which it has been transported largely by rivers. Although most river water is fresh to the taste, the amount of mineral matter carried in it every year is enormous, hence the ocean is being constantly enriched in these compounds. At the same time, only pure water is removed by evaporation.

Aquatic life. A great variety of plants and animals live in the oceans and lakes. Many types secrete calcium carbonate and other compounds either within themselves as skeletons and supporting structures, or around themselves as dwellings in which they live. Marine organisms, especially corals and lime-secreting single-celled plants called algae, build reefs of various shapes. The coral lives only in shallow waters, hence the reefs are built up from slightly submerged continental or island shores. Off the northeast coast of Australia, for instance, the Great Barrier Reef is 1,200 miles long. Some of the coral islands of the Pacific and the Bermuda Islands in the Atlantic are located where the surrounding ocean floor lies at great depth, but wells drilled on such islands have shown that the reefs have been built on top of submerged volcanic peaks.

Many other forms of animal and vegetable life living in the seas and lakes do not secrete mineral material.

GEOLOGIC PROCESSES

In addition to their role of supporting abundant organic life and creating definite types of climate, oceans and lakes are also important agents of erosion and deposition.

Movements of water. There are three types of movement in ocean waters: waves, tides, and currents. Most waves are developed by winds blowing across the surface of the water; the friction or drag of the wind against the surface piles it up in a series of arches separated by troughs. The greater the velocity of the wind, the higher the arches or waves. Most geologic work accomplished by wave action takes place during storms when the winds and the waves are high. Storm waves, the most important geologic agents, although they can appear in any season, are most frequent during the winter months. Waves are produced also by earthquakes. The sudden movement of rocks on the floor of the ocean may generate waves of great size. Waves produced by earthquakes occurring off the west coast of South America and off the coast of the Japanese islands have travelled across the Pacific Ocean. Still another cause of waves of unusual magnitude are volcanic explosions either beneath the sea or in coastal regions. The great destruction by waves following the explosion and collapse of Krakatoa in 1883 is described in Chapter 10.

Waves produced by earthquakes and volcanic explosions may be eighty feet and even more in height. The maximum height of those formed through wind motion is about fifty feet, but most waves are considerably lower. The depth below the surface of the water through which wave motion is felt varies, of course, with the size of the waves. A relatively quiet sea will affect the water for only a short distance below the surface; the maximum depth through which wave motion is transmitted is ordinarily no more than twenty-five feet, but in seas of unusual turbulence may reach as much as 200 feet. Below wave base the water is quiet and therefore not capable of performing geological work.

The ocean is never quiet. Though there may not be even a gentle breeze, waves will roll across the seascape due to agitation set up by earlier winds or to winds blowing elsewhere over the ocean. Hurricanes in the South Atlantic generate waves which travel many miles beyond the area visited by the storm.

Water waves constitute a form of energy. The wave crests and troughs move across the ocean surface, but there is very little forward movement of individual particles of water. Each particle of water describes a circular or elliptical orbit, the highest point of which is at the crest of the wave and the lowest point in the succeeding trough. When the water particle returns to the top of the orbit it is on the crest of the next wave. If the wind is blowing the particle does not return exactly to the same place because the water at the surface is driven by the wind in the same direction that the waves are moving, but at a much slower speed.

Rapid forward movement of water takes place when the water becomes shallow and the wave breaks. Breakers are caused by the retardation of the water particles involved in the wave motion as they drag bottom. The momentum at the top of the wave carries it forward, the front of the wave becomes concave, and it breaks. The water, impelled by the momentum which it possessed while at the top of its orbit in the wave, rushes forward onto the beach. The width of the breaker zone depends upon the gradient of the beach and the height of the waves. A gently sloping beach produces a wide zone of breakers. Large waves break at greater depths than small waves, so the distance off shore to the first breakers depends to some extent upon how much sea is running at the moment.

After the force of the breaking wave has spent itself, the water thrown upon the sloping beach obeys the law of gravity and runs back into the sea. Because some of the water originally came from the most distant line of breakers, an equivalent amount of water must be returned that distance. This returning current of water, known as the *undertow,* stays close to the floor of the sloping beach. It does not travel out beyond the farthest breakers.

Shore currents are set up by waves that strike the coast line obliquely, as is usually the case. Some of the water is not thrown onto the shore when the wave breaks but is deflected parallel to the shore. Succeeding waves, and waves farther down the beach, add to the longshore movement of water. Currents of this type are persistently produced where the prevailing wind direction lies at other than right angles to the shore line. They are also produced where headlands jutting out into the ocean cause some stretches of the coast to lie oblique to the prevailing wave direction.

The *tide* is a bulge or wave of great area caused by the gravitative pull exerted by the moon (and to a lesser extent by the sun). Ordinarily this great wave has insignificant height, but where its movement is retarded by shallow water or by narrow passes into estuaries or between islands the water piles up, and the movement of this impeded water creates *tidal currents* which may have considerable velocity.

Ocean currents are large-scale and continuous movements of water from one part of the ocean to another. The Japanese current of the North Pacific flows northward along the west side of that ocean off the coast of Japan, is deflected to the east and south by the Aleutian Islands and the Alaskan peninsula, and flows southward just off the Pacific Coast of North America. It turns west north of the equator and completes its circuit off the Japanese coast. The Gulf Stream of the North Atlantic starts north on the west side of the Atlantic, is deflected eastward off Cape Hatteras to the European coast, moves north into high latitudes, then west to the Greenland coast and south along the east border of North America, where it is known as the Labrador current. Both of these currents carry moderately warm water into northern latitudes and appreciably modify the winter temperatures of the adjacent land areas.

Erosion. Waves pounding against a coast are powerful agents of erosion and gradually drive the shore line back. If the sea floor is shallow, the waves break a considerable distance off shore and most of their energy is spent before they reach the shore line. On the other hand, if the water is deep, the waves break immediately against the shore line and the effect of their incessant drive is considerable. Where weathering has softened and loosened parts of the shore rock, small fragments will be sluiced away by the sea water thrown against the face of the rock. Wave water, dashing into cracks and other openings in the face of a sea cliff, may act as a piston, pushing the air into a small space at the end of the opening. This compressed air in turn pushes outward in all directions, tending to shatter the confining rock. If the rock is resistant and unweathered, grains of sand and even pebbles carried by the waves act as abrading agents as they are hurled against the cliffs. The rock fragments flung against the shore by the waves are themselves abraded to smaller size. Likewise the sand and gravel particles lying on the ocean floor within the zone where wave motion disturbs them are worn by incessant rubbing against one another.

Currents are much more important agents of transportation than of abrasion. However, undertow and longshore currents flowing down or along the beach after the shoreward surge of a wave tend to remove the loose material on the beach. And in a few localities, tidal currents move at such a velocity that they vigorously erode their channels.

Transportation. The methods of transportation in oceans are the same as in streams. Materials are carried in solution, in suspension, by saltation (a series of jumps), sliding, and rolling. The greater the velocity of wave or current, the heavier are the fragments that can be transported. This effectively sorts the sediment according to size.

Sediment is transported by wave action in two directions. A wave dashing up on the beach carries material with it which it drops toward the end of its forward surge. Then the water running back into the sea after the wave has spent its fury carries sediment with it. The coarse material is left high on the beach until pounding and abrasion by the waves has reduced it to particles sufficiently small to be transported outward. Sediment also is spread along the beach, where the prevailing winds or the presence of a projecting point causes the wave front to strike the beach at an angle. A wave that strikes obliquely carries material up onto the beach at an angle. When the wave recedes, the water draining into the sea moves directly down the slope of the beach with its load. The next obliquely striking wave picks up some of this material, and carries it up on the beach once more, but not to the same place. In such a manner, particles fine enough to be moved by wave action are transported laterally along the beach by following a zigzag trail.

The very fine material carried by the waters of a receding wave may be picked up by the undertow and carried in suspension out beyond the zone of wave agitation. A greater volume of sediment, however, is carried by shore currents. These not only transport materials obtained through wave erosion, but also distribute the sediment carried in by the entering streams. The slower moving currents transport material in suspension only, but the faster currents, such as those caused by tides in bays and inlets, are able to move particles of sediment by sliding, rolling, and saltation.

Deposition. Sediment entering the ocean follows the same rules of deposition that are in force elsewhere; a decrease in velocity of wave or current causes the load to be dropped. One favorable environment for deposition of sediment is at the mouth of a river, where the current of the entering stream is checked. The coarser material travels a relatively short distance, but very fine material, carried in suspension, may be transported several hundred miles out from the mouths of the larger rivers before coming to rest on the sea floor.

Currents moving parallel to the coast are checked where water deepens in the many indentations interrupting the smooth contour of the shore line. Therefore current-borne sediment will be deposited at the mouths of bays. In a like manner the seaward moving undertow encounters deeper water which checks its velocity so that the sediment is deposited.

Another form of deposition is by precipitation. If the water becomes supersaturated with a particular compound, due to excessive evaporation or other cause, grains of that compound come out of solution and settle onto the floor. In the past, thick deposits of salt, calcium carbonate, and other minerals have been formed in this manner.

Lastly, there is organic deposition. Some animals, especially the shellfish, remove calcium carbonate or other material from the sea water, with which to build shells or skeletons. These may accumulate into thick deposits.

RESULTS OF GEOLOGIC PROCESSES

Along shorelines, certain topographic features are developed by erosion, deposition, or both.

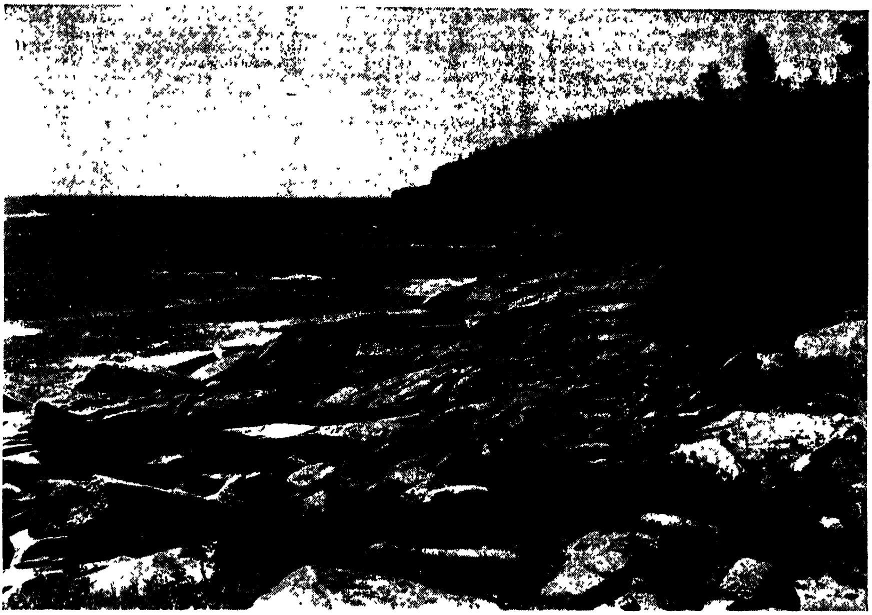

Fig. 91. Wave erosion of bed rock outcropping at water's edge. In time this coarse material will be broken into gravel, sand, and even silt by wave action. Acadia National Park. *By Allan Rinehart. Courtesy National Park Service, U. S. Department of the Interior.*

Erosional features. Normally the surface of the land adjacent to the coast slopes toward the ocean. Where the slope is steep, waves erode *sea cliffs.* After sea cliffs have been driven back far enough so that the upper part of the face is above the reach of waves, erosion continues by undercutting at wave level. When this undercutting is sufficient, unsupported masses of rock break away (Fig. 91). This debris, perhaps originally very coarse, is broken down by wave action until it is small enough to be carried away by undertow and shore currents.

At the base of the cliff, the waves erode a surface sloping gently out to sea, called the *wave-cut bench.* The agitation of the water above a wave-cut bench is so great that no sediment remains there permanently. When it is ground sufficiently fine to be moved, the material is carried beyond the seaward edge of the terrace.

A single storm may cause noticeable changes in the shoreline. Wind and wave damage done by the New England hurricane of 1938 was described on pages 46 and 47. The high winds of this storm created exceptionally large waves and drove them onto the shore where they caused great damage to works of man and natural features alike.

> On Napatree Beach, Westerly, Rhode Island, the storm waves destroyed the sea wall and a million dollars worth of property, swept the beach clear of its dunes, lowered it, extended it back into Little Narragansett Bay, and opened a gap 300 feet wide in it. At the height of the storm the beach was probably covered by between 5 and 10 feet of water. Sandy Point, adjoining Napatree Beach, was breached by two breaks, one 1,600 feet long and the other 900 feet. A continuous beach nearly 3 miles long was thus broken by the storm into three islands with more than half a mile of water between them.
>
> Other large breaks cut into Sandy Point in the past have been healed and it seems safe to say that these new breaks will in time also be filled.[1]

Wave erosion acts differentially just as do the other agents of erosion; softer rock is eroded with greater rapidity than resistant rock. This process produces many interesting, even bizarre, features along a coast line. Igneous dikes cutting the rocks of the coast in some instances are more resistant than the rocks they intrude, hence they form natural sea walls or promontories (Fig. 92). At other localities, these dikes are less resistant than the country rock, and waves have cut them away, forming caves. Sea cliffs of limestone also contain caves. Some of these caves were originally formed by ground water and have been exposed by wave erosion. In other cases, the caves have been made by waves through a combination of both physical and chemical erosion.

If the coast is composed of sedimentary rock layers of varying degrees of resistance, still other features are produced. Where the strata are flat-lying the sea cliff is horizontally fluted because the more resistant layers bulge out beyond the softer layers. If the strata are steeply tilted or vertical, the sea cliff becomes very irregular, because the soft rock layers form indentations and the harder layers promontories.

Differential erosion also produces islands, for the waves cut more actively along a zone of weakness across a promontory and eventually separate the point from the mainland. The zone of weakness may be a joint or fault plane (cracks in rocks described in Chapter

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[1] Nichols, Robert L., and Goldthwaite, Lawrence. Shoreline changes in Rhode Island produced by hurricane of Sept. 21, 1938 (abstract): Geol. Soc. America, Bulletin 49, No. 12, pt. 2, 1938, p. 1894.

11) or it may be less resistant rock, such as a dike of relatively soft igneous rock or a vertical bed of shale lying between harder strata. Joints are planes of weakness because of the existence of a crack permitting the penetration of surging sea water and the greater weathering of the rock along the joint crack. A single joint may extend all the way across a promontory, facilitating erosion which eventually separates the rocky point from the mainland. A preliminary stage in this process may be the cutting of an *arch* or *tunnel* at the level of wave erosion. Eventually the roof collapses, and a rock *stack* is separated from the mainland (Fig. 93). The sea, surging through the gap, gradually widens it.

Neither tidal nor ocean currents ordinarily have sufficient velocity to cause submarine erosion. However, these currents may move sufficiently fast to transport sediment in suspension to quiet water

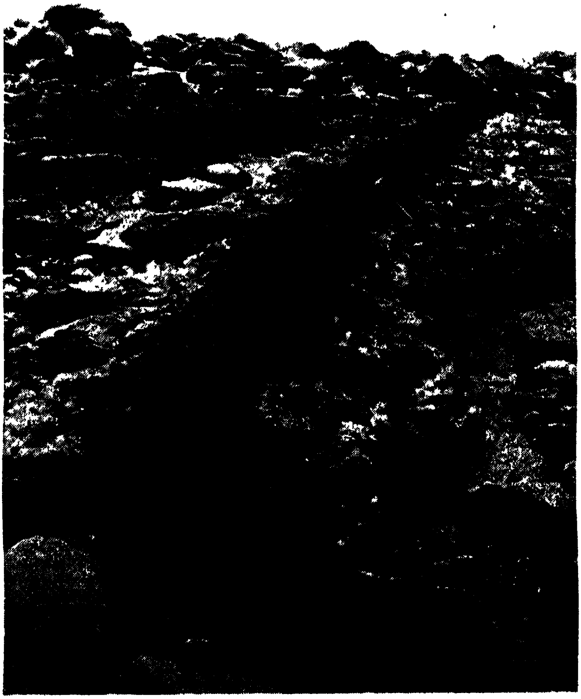

Fig. 92. Resistant igneous dike cutting less resistant sandstone. Southwest coast, Island of Arran. *Courtesy Geological Survey and Museum, London.*

where it is dropped. They also transport marine life of the floating type.

Submarine canyons. Still very much of a mystery to geologists are canyon-like depressions in the outer part of the continental shelf and in the continental slope. A few have been known for many years through depth soundings along coast lines; the development of the echo method of sounding ocean depths has increased the number of known "canyons" to over a hundred. In form, these gorges closely simulate mountain canyons eroded above sea level.

The submarine "canyons" are incised in the sediment and bed rock of the continental shelves, with their mouths opening out onto the ocean floor near the base of the continental platforms. Some connect at their upper ends with trenches dug by rivers, but others head in the smooth floor of the continental shelf, several miles from land, with no apparent connection with the drainage off the adjacent land.

The largest submarine canyon known is a continuation, beneath the sea, of the valley of the Congo River in Africa. On the other hand, the Mississippi River does not have a submarine canyon opposite its present mouth, although a comparatively small one exists

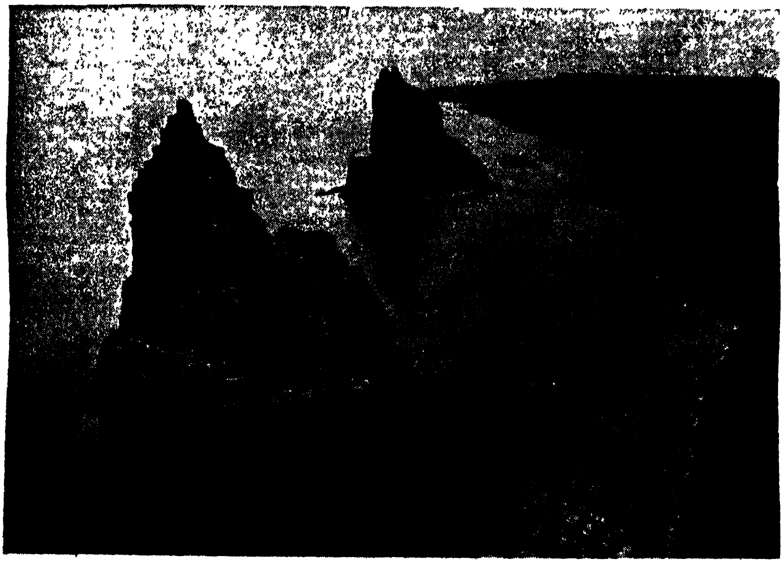

Fig. 93. Stacks of sandstone separated from mainland by marine erosion. Duncansby, Caithness. *Courtesy Geological Survey and Museum, London.*

about forty miles southwest of the present delta. The submarine canyon extending seaward from the mouth of the Hudson River is in places five miles from rim to rim and 3,600 feet deep.

> A river flowing down this canyon would be a fearful and wonderful sight indeed, because it would run down an average slope of 150 feet to the mile, 12 times the average gradient of the present Colorado River flowing in the Grand Canyon. This is only one of a dozen similar canyons found between Cape Hatteras and the eastern limit of Georges Bank, 200 miles east of Cape Cod.
>
> Coastal shelves are very narrow off some coasts, as for example portions of the Pacific Coast of the United States and Alaska. One of the mightiest canyons known is found in Monterey Bay, California, and the head of this remarkable canyon is less than half a mile off the beach. This canyon of Monterey Bay, if stripped of its blanket of ocean, would certainly rival the scenic grandeur of the greatest of our western canyons.[2]

The mystery of these "canyons" is their origin. To have been carved by rivers, the continental shelves must have been elevated 12,000 feet above sea-level, or sea-level depressed several thousand feet below its present position, views which most geologists are loath to accept. It is doubtful if ocean currents ever have attained the velocity necessary to carve them. Some have suggested the "canyons" may have been formed by water loaded with sediment which slid down the slopes at the edges of the continental platforms during the last glacial period. None of the present explanations is acceptable to a majority of geologists.

Depositional features. The ocean is the site of deposition of sediment which is both won by the ocean itself through wave erosion and introduced by the rivers that drain the continental areas and by other agents such as winds, glaciers, and gravity fall. Most of the sediment is deposited near shore where the sea floor lies at shallow depths, but some deposition takes place in the much deeper basins.

The sediment introduced into the ocean by the rivers meets relatively quiet water at the river's mouth and in many cases forms a *delta,* which grows seaward and on each side of the river where space is available. Some rivers have extended the land many miles seaward through delta building. Part of the delta may properly be considered a river deposit because the sediment is laid down above sea level where the stream gradient is very slight. A great quantity of river sediment is carried out beyond that part of the delta that lies above the surface of the ocean and is either deposited on top of the submarine extension of the delta or out on the edge of the delta where it slopes down to the ocean bottom. The very finest material is carried out beyond the delta proper where it either settles onto the sea floor or is picked up by laterally moving currents and carried parallel to the coast line, perhaps for many miles, before it is deposited.

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[2] Smith, Paul A., Submarine Canyons; Radio talk, April 24, 1939. Published by Geological Society of America in *Frontiers of Geology;* Ten papers originally prepared for fifteen-minute radio addresses by Fellows of the Society, 1938-39. 48 pp., December, 1939. See pages 11-14.

Beaches are present along the shore line except where the water immediately offshore is very deep. Rivers emptying into the ocean nearby contribute some sediment to the beaches, but most is generated by wave erosion along the coast. The waves attack promontories with greatest vigor, and the sediment broken from them is strewn for many miles along adjacent beaches by currents.

Sediment on a beach tends to become segregated by size and weight. Most of the boulders and cobbles which cannot be moved by the undertow are found along the upper or landward margin of the beach. Beyond and below the boulder fringe, if there is one, is sand, while below the level of most wave agitation, the finest sediment (mud, silt, and clay) has opportunity to settle.

Exceptional environments cause the formation of special types of beaches. Along irregular coast lines, beaches of appreciable width are confined to the heads of bays (Figs. 94 and 95). Some of the sediment in such *bay-head beaches* may have been brought there by a stream emptying into the head of the bay, but usually most of it has been carried by shore currents. Wave erosion of the headlands at the mouth of a bay produces sediment which eventually comes to rest in the relatively quiet water at the head of the bay.

In the case of an advancing sea, the beach sediment is a veneer temporarily covering the shoreward section of a wave-cut beach. As soon as the sediment is ground fine enough, it is carried seaward and dumped beyond the edge of the wave-cut beach, producing in time a *wave-built terrace*. The sloping surface of the beach merges with that of the terrace.

Spits are elongate bodies of sand or other sediment which extend from shore out into open water where the coast line makes an abrupt change in direction. An example is to be found at the mouth of many bays where shore currents have built spits from one point

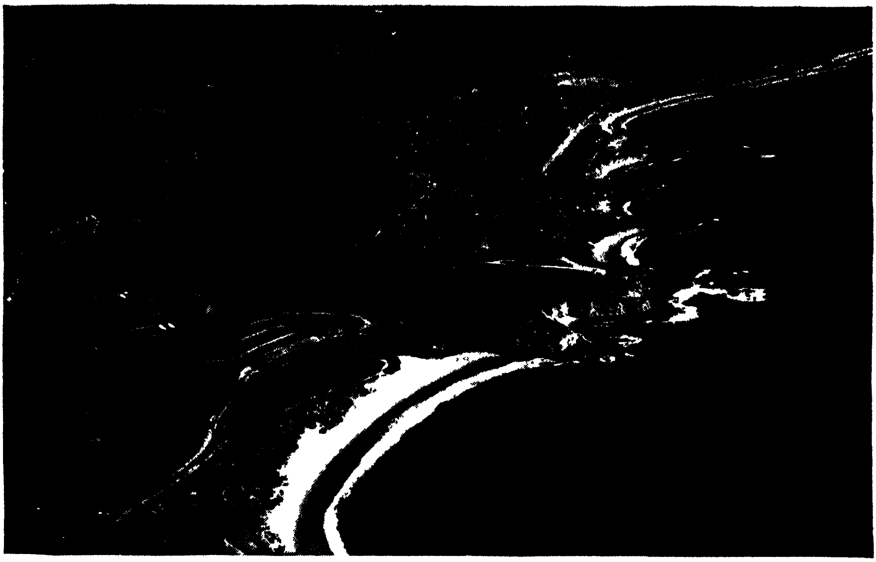

Fig. 94. Bayhead beaches between rock promontories. Laguna Beach, California. *By permission Spence Air Photos.*

Fig. 95. Bayhead beaches in more advanced stage. Beach is wider and extends, with diminishing width, to point. Antelope Island and Promontory Point, Great Salt Lake, Utah. *By permission Spence Air Photos.*

across toward the other point or from both points headed toward each other. In some instances spits completely shut off the harbor, "landlocking" a body of salt water. Such spits are called *bay bars.* The deposition of sand in spits is due to the sudden slowing down of a shore current where the coast line turns abruptly into a bay. The current sweeps straight on into the deep and relatively quiet water at the mouth of the bay. Another type of a spit, called a *tombolo,* grows from a headland out toward a near-by island until it connects the island with the mainland (Fig. 96). In some instances bars project from each side of a headland and converge at the island. Tombolos owe their origin to the setting up of shore currents by oblique waves striking the sides of a promontory at such an angle that the currents are deflected toward the point. The sediment carried by these currents is dropped in the open water beyond the end of the promontory because their velocity is suddenly lessened.

Offshore bars or *barrier beaches* are built parallel to the coast line, from which they are separated by a lagoon of shallow water. Normally there are shallow openings into the lagoon at various places along the bar. Barrier beaches extend for hundreds of miles along the Atlantic and Gulf coasts. These bars are formed only

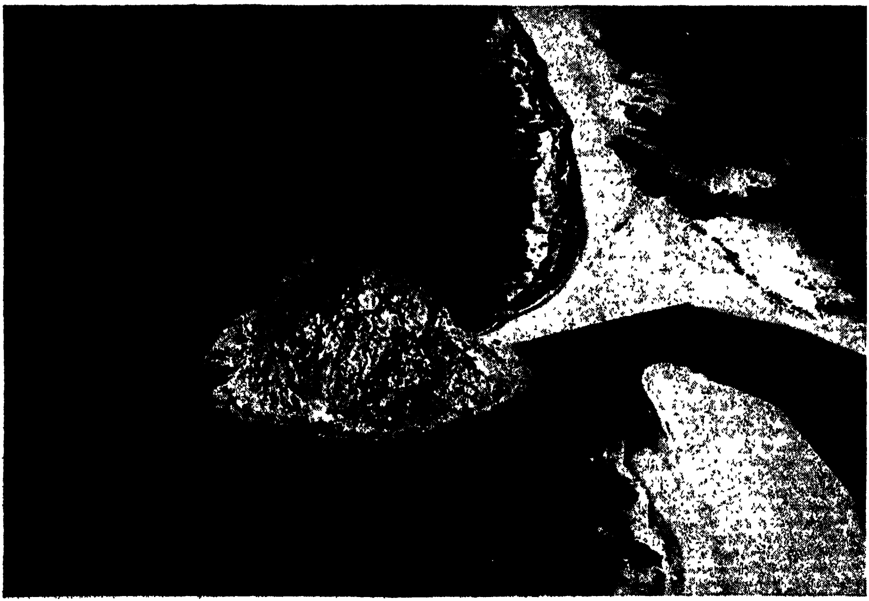

Fig. 96. Tombolo, tying island to mainland. Estero Bay and Moro Rock, California. *By permission Spence Air Photos.*

where the water offshore is shallow and where the beach is floored with loose sand. The incoming waves drag on the shallow bottom, agitate the sand, and gradually sweep it up into a low ridge parallel to the shore. After wave action has built the bar so that it stands above low tide level, the wind dries the sand and blows it into dunes so that eventually the barrier beach becomes an *island* even at high tide. Most barrier beaches are so low that they can be crossed by high storm waves and so are not suitable sites for settlement.

Beach placers. Where valuable minerals are present in stream beds near the shore, some of the grains are swept into the ocean, where shore currents pick them up and distribute them along adjacent beaches. Placer minerals brought to the sea by streams draining the southern Appalachians of Georgia and the Carolinas are found along the northern coast of eastern Florida. Similar deposits containing monazite, a thorium mineral used in the manufacture of incandescent gas mantles and as a source of atomic energy, are found on the coasts of Brazil and India. Gold occurs in the beach sands of southwestern Oregon and at Nome, Alaska.

Atolls. An atoll is a ring-shaped coral island enclosing a lagoon. Many of the islands of the south Pacific are atolls. Three conditions are necessary for atoll formation: (1) a volcanic peak, originally rising from the ocean floor to a point above sea-level, (2) reef-building corals and (3) slow submergence of the volcanic cone. The corals can exists only in shallow waters; they originally girdle the volcanic island with a fringing reef. As submergence proceeds, the corals build upward from their original site, producing a barrier reef with a lagoon between it and the volcanic cone. Continued submergence will result in the disappearance of the volcanic peak beneath the waters of the lagoon.

Deep oceanic deposits. Most of the sediment entering the ocean from the bordering lands is deposited in the shallow waters on the continental shelves, and on the continental slopes. Where these shelves are narrow and the slopes are relatively steep, sediment from the continents will come to rest on the floors of the ocean basins. This is the case in several places around the border of the Pacific Ocean where much of the river-borne sediment and wave eroded material overflows the short deltas and narrow beaches and covers the adjacent ocean bottom. Some distance out from the continents, however, very little land sediment is available for deposition. A relatively small amount of wind-borne dust, debris carried in icebergs, and volcanic ash settles onto the surface of the sea and sinks to the bottom. Minute one-celled animals live on the deep sea bottom in places and make shells of calcium carbonate and of silica which accumulate into deposits of *calcareous* and *siliceous ooze.*

Oceanographers not only have mapped the topography of the ocean floors, but have also collected thousands of sea-bottom samples. Dr. Louis Agassiz, in 1870, after detailed study of many such samples, was able to announce that the ocean basins (and the continental areas) have occupied the same general positions that they occupy today since earliest times. This conclusion, of fundamental importance to earth historians, was made possible by comparing forms of animal and plant life dredged from the floors of the deep oceans with the fossils found in the rocks of the continental areas.

Oceanographers have developed several ingenious devices for obtaining cores of sea floor sediment. A piston core sampler, which is lowered to the sea bottom by a cable, has taken cores up to 70 feet in length. The core presents an accurate cross section of the submarine sediment from which many conclusions concerning the past history of the earth can be drawn.

> Through the ages the ocean has been receiving the material eroded from the continents, the chemical substances dissolved by the rains and the dust and volcanic ash borne by the wind. As these things changed in character or amount they left their record in the ocean's bottom. The sharp pebbles and coarse sand brought by the ice contrast markedly with the fine flocculent burden of unhurried rivers. This record has been accumulating during many changes on the neighboring continents and during many changes in the water above.[3]

Vertical fluctuations of sea level. One is apt to consider "sea level" to be a rather stable plane below which all land to which the sea has access is submerged. However, many parts of the continental areas are floored with hundreds and even thousands of feet of sedimentary rocks containing fossils of marine organisms. Obviously, the sea at one time covered those areas. As a matter of fact, most regions of sedimentary rock have been inundated not once, but many times.

The present is a time when the greater part of the continental platforms lie above sea level, although marginal seas overlap the continental shelves to various distances. In places, such as the Gulf and South Atlantic coasts of North America, the marginal seas are wide. Vertical changes in sea level are no doubt taking place today just as in the past. Changes of several hundred feet have occurred quite recently in the earth's history, some of them since man has lived on the globe. Such changes are usually slow and not readily noticed. If sea level were to rise to a position half way up the sides of the Empire State Building in New York City, both Louisville and Saint Louis would become seaports on the Gulf of Mexico. Most of the State of Mississippi and all of Louisiana and Florida would lie under the ocean. Much of Europe would be submerged.

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[3] Piggot, Charles S., "Core Samples of the Ocean Bottom and Their Significance," *Scientific Monthly*, Vol. 46, 1938, p. 206.

There, no doubt, have been times in the past when such vertical fluctuations were world wide so that the sea rose or fell on all continents. For example,

> When the great continental glaciers formed over parts of North America and Europe, the water thus piled up on the lands in the form of thick ice caps must have been evaporated from the oceans to give the necessary snow and ice. Hence sea level must have fallen, perhaps a few hundred feet, perhaps more. When the ice caps melted and the water flowed back into the ocean, sea level must have risen. But unfortunately the weight of the ice piled up on the continents probably caused those parts of the land to sink unevenly. Melting of the ice apparently allowed the land areas relieved of this load to rise, but to rise unequally.[4]

Most fluctuations are probably due to vertical movements of parts of continents rather than to worldwide changes in ocean level. The vertical movements are caused by deep-seated movements of the earth's crust (diastrophism). The continents have tilted so that one part has become inundated while another part has risen out of the sea.

There are many examples of prehistoric but nevertheless geologically recent changes of level about the continental borders. Where emergence takes place the beaches are elevated, making terraces. The sediment on the raised beach contains shells of modern or practically modern marine organisms. Because of the unconsolidated character of beach material, elevated beaches cannot exist for very long, for eventually the forces of erosion will destroy them. If the ocean waves were attacking bed rock before the emergence, an elevated wave-cut terrace will result. Marine terraces of this type terminate abruptly at the shoreward end against the foot of a sea cliff. An elevated sea cliff may have any of the characteristics of one at the water's edge, including caves and nearby stacks. Both wave-cut terraces and sea cliffs, being composed of consolidated rock, will withstand the forces of erosion longer than an elevated beach. However, they, too, will be destroyed in time.

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[4] Johnson, Douglas, *Shifting Ocean Levels*," Radio address, May 1, 1939. Script published by Geological Society of America. See footnote, page 193.

Every ocean is bordered in places, in some instances for many miles, with elevated beaches or wave-cut terraces and sea cliffs. In a few localities a series of such elevated *strand lines,* one above the other, occurs. Each of these levels marks a former shore line, a time of temporary stability during a slow uprising of the coastal belt. The lowest terrace is, of course, the youngest; a subsequent elevation will add the present beach to the series of older strand lines. The coast at Nome, Alaska, is an outstanding example of a series of beaches. There three successive elevated beaches lie above the present one at elevations of 22, 38, and 78 feet. In addition, out beyond the present beach are two submarine beaches, one 20 feet and the other 34 feet below sea level. Obviously the Seward Peninsula in the vicinity of Nome was recently elevated in a series of upward movements with a beach formed during each period of quiescence. After at least five such beaches had been built the direction of movement was reversed and two of the strand lines were submerged. The Nome beaches are of additional interest because they are gold bearing. Gold was discovered in the sands of the present beach in 1897, and during the the years that followed the remnants of the elevated beaches and the two submarine beaches were discovered and found to be gold-bearing also.

As a general rule an elevated coast is smooth (no promontories or bays). The reason is that deposition in the ocean adjacent to shore has created a gently sloping beach and sea floor for some distance out from the water's edge. Naturally when such a strand line is elevated the new water-land contact will be a fairly straight line. An exception occurs, of course, where the offshore depths previous to emergence were great and consequently deposition had not produced a sloping beach and ocean floor.

Normally, also, the water offshore following elevation is shallow. This condition is conducive to the formation of barrier beaches, so such sand bars are additional criteria of recent emergence. Barrier beaches are not universally present, however, because if the water offshore was deep initially it may still be deep enough following an elevation of small magnitude that the waves fail to drag bottom before reaching shore.

Depression also has occurred in many localities during the recent past. Of course many of the usual shore line features, such as wave-cut and wave-built terraces and sea cliffs, may become so deeply submerged that they are not readily observable. Other easily recognizable criteria of submergence exist however. The lowest points along a shore are the mouths of river valleys, and, when a coastal area is depressed, the sea water extends up the valleys for varying distances, making *bays*. Such famous harbors as San Francisco Bay, Puget Sound, New York Harbor, and Liverpool Harbor are *drowned* river valleys. San Francisco Bay owes its unusual shape to the fact that two river valleys, the Sacramento and the Santa Clara, used to join a short distance from the ocean, and the combined rivers flowed out to sea through what is now the Golden Gate. The California coast has been depressed a sufficient depth to drown the river valleys for a considerable distance beyond their junction.

A drowned river mouth is known as an *estuary*. Hills rising above the valley floor become islands if they are not completely submerged. The rocky islands in San Francisco Bay were formerly hills, and the great bridge that runs from San Francisco to Oakland tunnels through one of the islands en route. The islands in New York Harbor owe their origin to the drowning of the lower Hudson River valley.

A special type of bay, the *fiord,* is common along the coasts of Norway and Alaska. A fiord is a fairly straight salt-water inlet with precipitous sides. Valleys merge with fiords at the landward end, and in northern latitudes many of the valleys are occupied by glaciers that may come clear down to the sea. Fiords are without doubt drowned river valleys, but the shape of the valley has been modified by glacial erosion. In most instances the valley was carved by ice into a U-shape before submergence. However, some drowned river valleys may have been converted into fiords through glacial movement after submergence. Ice moving down a valley from mountains immediately adjacent to the coast could presumably push a considerable distance out into the water where it would modify the shape of the valley walls, giving them the typical precipitous sides of a fiord.

As a usual thing, depressed coastal areas exhibit a very irregular shore line. Most continental borders are cut by river valleys, the drowning of which produces a multitude of bays. Likewise, in most cases, submergence produces deep water offshore. An exception, of course, occurs where a low-lying coastal area is submerged. The best harbors are ordinarily found where shore lines have been submerged and the poorest harbors occur along emergent shore lines. The north Atlantic coast of North America was submerged and in consequence many fine harbors are to be found in eastern Canada, Maine, Massachusetts and as far south as the drowned valley of the Chesapeake. The south Atlantic coast, on the other hand, has recently emerged, and good harbors there are few and far between.

A drowned coast line affords an ideal environment for the formation of bay-mouth spits and bay-head and tie beaches. The presence of these features is consequently evidence of recent submergence.

Physiographic age of shore lines. Shore lines can be designated by physiographic age as can rivers, valleys, and continental regions. The objective of ocean work is the complete destructtion of the land by wave erosion and the deposition of the fragments and the sediment so gained on the sea floor. No continents have been destroyed by wave action, but their circumferences have been decreased. Small islands have been completely destroyed, in a few instances during historic time. Only two terms, youth and maturity, are used to express relative age of coast lines. In physiographic nomenclature old age refers to the accomplishment of a task, and no shore line can have reached old age as long as there is a shore to attack. The criteria of youth for a submerged coast are quite different from those applying to an elevated coast. Likewise the stages between youth and maturity differ markedly, but when full maturity has been reached the coast lines are very similar in appearance.

In early youth the outstanding characteristic of a submerged coast is an irregularity of shore line. The mouth of every river has become a bay, and even the very small ravines and the valleys occupied by temporary or intermittent streams make indentations in the coast line. The divides between the drainage basins become headlands. The degree of unevenness of the coast line is dependent upon the initial relief of the land and the amount of the submergence. The submergence of a region in the mature stage of running water erosion will result in a much more jagged coast line than if the region had reached old age before being submerged.

As a submerged coast approaches maturity through the work of the ocean, a series of changes takes place. The headlands suffer direct attack from the waves and are driven back. Differential erosion on the sides of a promontory may cause the separation of the point into an island. Such islands are subject to attack by the ocean waves from all sides and in consequence are relatively temporary features. The sediment obtained through wave action on the headlands may be dragged out into deeper water by the undertow and deposited there as a wave-built terrace, or it may be swept parallel to the shore by currents and deposited elsewhere.

The water in the bays, on the other hand, is comparatively quiet, and consequently deposition is more important there than erosion. Bay-mouth spits may form at the seaward end of the bays, tending to close off the estuaries. However, if a stream with an appreciable volume of water enters the head of the bay, it will be impossible, because of the unceasing outward current of water, for the bar at the mouth completely to close off the bay. Some bays, however, receive no more water than can be taken care of by evaporation, in which case the bar at the mouth may extend all the way across. Examples of this occur along the shore of Martha's Vineyard, an island off the southeastern coast of New England. The island was cut by a number of valleys, which became bays when submergence took place. However, the drainage area of each valley above the present water level is so small, because of the small size of the island, that insufficient water enters the bay to prevent complete closing off by bay-mouth spits.

Concurrent changes take place inside the bays. They tend to *silt up* through the introduction of stream-borne sediment, especially at the upper end of the bays. Bay-head beaches are also built of sediment eroded from the points and carried to the head of the bay by shore currents.

An intermediate stage in the attempt to obliterate a bay is the tying of islands out in the bay to the nearby shore by means of tombolos. An outstanding example of this is Boston harbor, where several islands have been connected to the shore by sand spits. The mouth of this harbor is so wide and the water so rough that bay-mouth spits have not yet had opportunity to form. The tie beaches inside the harbor give the impression that the ocean is first attempting to close off the inner harbor, after which it will move out and close off the outer harbor.

These various processes continue until maturity is reached. The methods pursued are the same whether the rock along the coast is granite or glacial drift, but in the latter case much faster progress is made. The bay-mouth spits of Martha's Vineyard owe the relative rapidity of their formation to the fact that the island is composed of unconsolidated glacial debris.

A submerged coast has reached full maturity when the exposed shore has been eroded to a smooth line and at the same time the bays have either been filled up or closed off by spits, or both, so that they no longer make indentations, but coincide in position with the rest of the coast line. At full maturity the water is sufficiently deep offshore so that the waves can attack the land directly. Erosion continues fairly evenly with the theoretical goal the removal of all the rock material that lies above the wave base.

An emergent coast follows an entirely different sequence in proceeding from youth to maturity. If the water offshore was deep previous to the uplift, there will be no lasting change in physiographic age, for the ocean will soon destroy the narrow beach and renew the attack on the old shore. Examples of this are found on the shores bordering the Pacific. However, if before emergence the continental platform extended on out beneath the waters of the ocean for a long distance, or if the ocean had constructed a wave-cut and wave-built terrace of great breadth, and the emergence was not sufficient to expose the continental margin or the edge of the terrace, the water will be relatively shallow offshore and the coast line smooth following emergence. Under these somewhat special conditions a very distinctive cycle of ocean shore physiography is followed. The first stage is the building of a barrier beach by methods which have already been described. Examples are to be found along the Atlantic coast from New Jersey to Florida and along the Gulf coast, especially in Texas. Single barrier beaches in some instances extend for several score miles, and a series of such beaches may be several hundred miles in length. One effect of the building of a barrier beach is to smooth off a shore line which may previously have been slightly indented.

As erosion of an emergent coast of this type proceeds from youth into maturity, the barrier beach is driven in toward shore. Building a barrier beach deepens the water offshore, making the beach open to direct attack by the waves. Waves and onshore winds slowly move the barrier toward the mainland. At the same time the lagoon lying between the barrier beach and the shore tends to silt up with sediment. Such a coast reaches maturity when the barrier beach has been driven onto the mainland shore and the lagoon destroyed.

This achievement produces sufficiently deep water offshore so that the waves can attack the land directly, and they begin their task of destroying all land above wave base just as do the waves on a depressed shoreline that has reached full maturity.

The physiographic age of submerged and emerged shore lines affects the utilization of a coastal area by man. For example, the drowned mouth of the Columbia River does not make as valuable a harbor as do some of the other drowned valleys of the Pacific Coast because of the relatively advanced age of the local shore-line physiography. A partially submerged bay-mouth bar has been formed, which tends to block the harbor and handicap navigation. The Government has built jetties and dredged the channel in order to maintain a pass for large vessels. Drowning of the British Columbian and Alaskan coasts has inundated a series of valleys parallel to the shore line and created hundreds of islands, some of them, such as Vancouver Island, of considerable size. The so-called "inside passage" from Puget Sound to southeastern Alaska occupies these drowned valleys between the islands and the mainland so that boats making this voyage need pass through very little open water.

Although emergence of a region that is shallow offshore produces a scarcity of good harbors, the lagoons lying between the barrier beaches and the mainland may make a sanctuary for small craft. Light draft boats can follow an inside passage of this type from New York to Florida with the help, here and there, of man-made canals. Similar travel is possible for many miles along the Texas coast.

LAKES

Distribution. The relatively small depressions in which lakes are found are recent in age. The distribution of lakes depends upon the presence of geological activities that have produced depressions. Also necessary, of course, is the existence of sufficient rainfall so that the depression will contain water. In arid regions the normal position of the water table may be below the bottom of existing depressions, in which case the depressions hold water only immediately following a rain. Such lakes are *temporary.* In regions where the water table fluctuates seasonally, lying above the bottoms of the depressions during the wet seasons and sinking to lower levels during dry seasons, *intermittent* lakes occur.

Running water does not have a scooping effect, so closed depressions are impossible as the result of normal erosion by this agency.

However, a few lakes do result through the activity of running water (Chapter 5)—for example, oxbow lakes, which are due to the abandonment of meanders. The greatest number of lakes occur in depressions formed through the activity of glaciers (Chapter 6), particularly in the marginal deposits of the great ice sheets which at one time covered parts of North America and Europe. Not only are these deposits so uneven on their surfaces that they contain thousands of closed depressions, but also they dammed the preexisting drainage to such an extent that waters were impounded into lakes in many places. Because of the effects of glaciation, most of the lakes of the world occur either in high latitudes, especially in the northern hemisphere, or at high altitudes.

Local geologic conditions have created lakes in other parts of the world. Volcanoes (Chapter 10) and movements of the earth's crust (Chapter 11) produce depressions which are to be discussed in following chapters. Lakes occurring in wind-scooped depressions (Chapter 3), and in depressions created by sinks and land sliding (Chapter 7), have already been mentioned. Shore-line lakes were described earlier in this chapter.

Depths. Contrary to local traditions, which have it that many lakes are "bottomless," most lakes are comparatively shallow. A few lakes, such as Lake Chelan in the Cascade Mountains of Washington, which occupies an elongate basin formed by the deep scooping of a mountain valley glacier, exceed a thousand feet in depth. However, there are no lakes comparable in depth to the oceans.

Composition. The water of most lakes contains very little mineral matter. Outstanding exceptions are salt lakes, which are discussed in the following paragraph. Fresh-water shellfish are relatively uncommon in lakes, but other forms of life may be abundant. Some lakes, especially shallow ones in humid regions, support a luxuriant growth of plant life.

Salt lakes. Salt lakes occur both along the coast, where arms of the sea have become separated from the ocean, and in interior regions. Naturally, the water is salty where a part of the ocean has been trapped. In many cases, however, shore-line lakes tend to become brackish or even fresh because they drain into the sea and at the same time receive fresh water from entering streams. On the other hand, if there are no entering streams of any magnitude and additional increments of sea water are occasionally received through exceptionally high tides and storm waves, the shore-line lake water tends to increase in saline content because evaporation is constantly removing pure water, and salt in sea water is being added at irregular intervals.

Some salt lakes, such as Great Salt Lake in Utah, owe their salt content to a combination of circumstances. The water in such lakes may have been fresh originally but has gradually become saltier and saltier because inflowing streams, even though "fresh" to the taste, constantly bring in mineral matter, especially salt, in solution and because, at the same time, water in the lake is disappearing through evaporation. Lakes of this sort are impossible where the water can drain out either by way of surface outlets or through seepage. Another very important control in the formation of salt lakes of this type is climate. Evaporation must be sufficient to take care of all the entering water, otherwise the depression will fill up and overflow. Great Salt Lake used to be a fresh-water lake draining down Snake River to the north, but because of a climatic change it dwindled so that eventually the lake surface sank below the level of the outlet and subsequently the water became strongly saline.

Prehistoric lakes. Although most of the water-borne sediment deposited on the continents in the geologic past was deposited in marine waters (epi-continental seas), the contained fossils testify that large lakes also existed at various times. Furthermore, the presence of abandoned, but obvious, shore lines, now high and dry, are evidence of lakes in relatively recent geologic time, see Figs. 97 and 98. Many of these isolated seas have been mapped by geologists and given names. Examples are: Lake Algonquin, a predecessor of the present Great Lakes; Lake Agassiz, an enormous lake covering parts of what are now Minnesota, the Dakotas, and Manitoba; Lake Bonneville, the large fresh water ancestor of Great Salt Lake; and Lake Lahontan, most of which was in Nevada.

GEOLOGIC PROCESSES AND RESULTS

With the exception of tides and tidal currents, the same processes at work in the oceans operate in lakes. Naturally the results vary greatly, depending upon the size of the lake and upon local conditions. The shores of Lake Superior, the largest of the Great Lakes, are under almost ceaseless attack by the waves. Therefore, many of the features of ocean shores, such as wave-cut cliffs, beaches, and rock stacks are to be found around the edges of this lake.

Ice ramparts may occur on the shores of lakes in regions of cold winters. These are walls of rock material produced by the pushing of lake ice against the beach shingle. In extreme cases even summer cottages have been destroyed by the slow but powerful on-shore movement of lake ice. The creeping, pushing mass is caused by expansion of the ice or by wind. The former is applicable only in the smaller lakes. During the warmer daylight hours the ice expands and pushes shoreward. At night, contraction and cracking take place. The water moving into the cracks immediately freezes, so that a greater area of ice, for any given temperature, is the result. The following day the expansion will cause this larger mass of ice to move farther shoreward; this process can continue as long as the subfreezing temperatures persist. The ice push resulting from wind action takes place after a thaw has created a lane of open water out in the lake. A strong on-shore wind will create an ice jam which may be driven onto the shore with irresistible force.

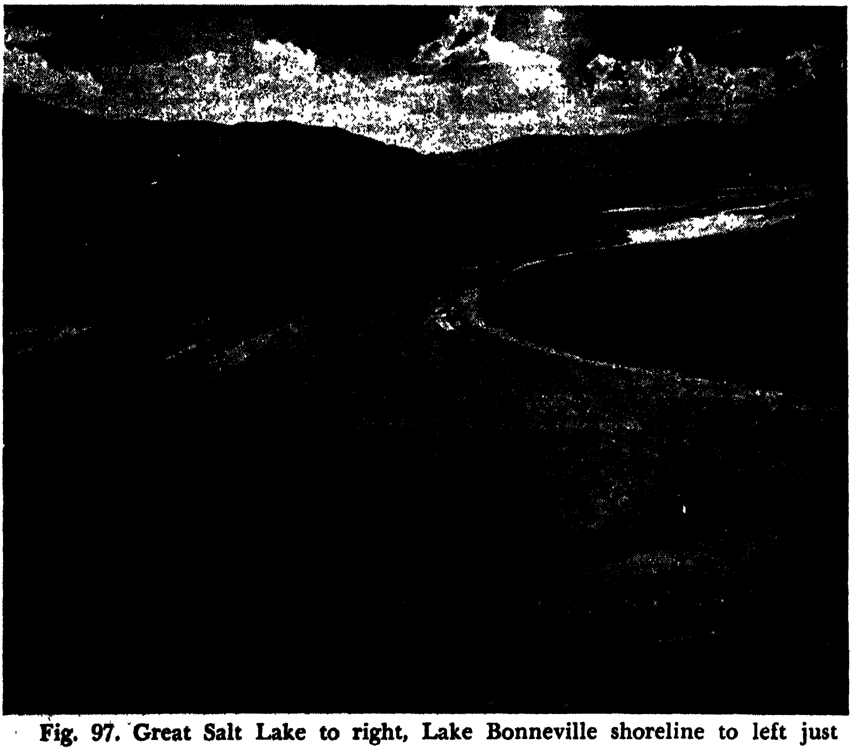

Fig. 97. **Great Salt Lake to right, Lake Bonneville shoreline to left just above top of highest smelter stack.** ***By permission Spence Air Photos.***

Streams entering lakes may build deltas, just as rivers do on entering the ocean. Materials brought in by rivers or obtained by erosion along the shores may be transported by shore currents until deposited on the lake floor.

The temporary nature of lakes was mentioned in the introductory paragraphs of this chapter. Most lakes are eventually destroyed either by being completely filled with sediment (some fairly large reservoir lakes have "silted up" in a few years) or by downward cutting of the outlet stream. However, some lakes are destroyed by complete filling by vegetation. These are known as *peat-filled* lakes.

SHORE EROSION CONTROL

Storm waves have caused damage of enormous magnitude to shore property. Some degree of success has been obtained in combatting these natural forces, by constructing sea walls, breakwaters, or

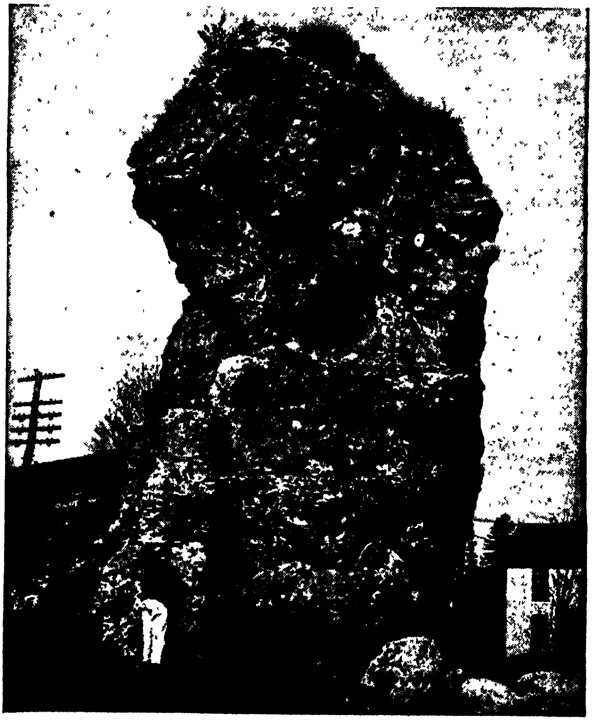

Fig. 98. Breccia stack formed by wave action of ancestral Great Lake. Present shoreline is at much lower elevation. St. Anthony's Rock, St. Ignace, Michigan. ***Courtesy Michigan Geological Survey.***

groins. *Sea walls* are masonry dikes erected on shore against which the waves spend their fury. They are constructed of reinforced concrete or of great stone slabs. Their purpose is, of course, to protect the land and structures on shore from being washed away by the surging waves. They have to be very strong and ponderous features if they are to withstand indefinitely the pounding of winter storm waves.

Breakwaters are aptly named. They are long, low masonry walls built offshore for the purpose of "breaking" the waves so that much of their energy is dissipated before reaching the shore. *Groins* are similar walls, but they are built at right angles to the beach line, extending from the shore some distance out into the water. They cause waves approaching shore at an angle to break prematurely, and also prevent attack by long shore currents. At the same time, sediment is retained between the groins, thereby decreasing the depth offshore and causing earlier breaking of the waves. Both breakwaters and groins, as well as sea walls, are vulnerable in time to wave erosion.

CHAPTER 9

Sedimentary Rocks

SEDIMENTARY ROCKS ARE COMPOSED EITHER of materials derived from older rocks or of accumulated organic matter. The original sediment in some instances was windborne or glacially transported material, dropped on the surface of the land. By far the greatest volume of sedimentary rock, however, was deposited in bodies of water, in most cases on the sea floor. The material thus deposited may be *clastic,* consisting of particles of pre-existing rock which were transported through the physical force of moving water, wind, or ice, or it may have been *precipitated* from water in which it was dissolved, or it may be of *organic* origin, consisting either of carbonaceous matter or of chemical compounds removed from the surrounding water by aquatic organisms. Sediment becomes consolidated sedimentary rock through processes of *lithification* which will be described subsequently.

The most abundant rock at the earth's surface is sedimentary. It has been estimated that about 75 per cent of the area covered by the continents is floored with sedimentary rock, the balance with igneous and metamorphic rocks. In the United States, by far the greater part of the thousands of square miles drained by the Mississippi River and its tributaries is covered with sedimentary rock. Similar rocks also occur, interspersed with igneous and metamorphic rocks, along the Atlantic coast and west of the Continental Divide. However, the sedimentary rocks occur in what is actually a relatively thin skin or veneer on the earth's surface; they are everywhere underlain by a many times thicker shell of igneous and metamorphic rock. The thickness of the sedimentary rock veneer varies widely. Over about 25 per cent of the land surface it is not present at all; elsewhere the thickness ranges from a few hundred to a few thousand feet, although in a few places it has been estimated that the sedimentary rock section is as much as 30,000 feet thick.

broken down into grains of *sand,* the readily altered mineral constituents have decomposed and disappeared so that only the inert quartz remains in any great abundance. Finer than sand is *silt,* and finest of all is *clay.* The feldspar, which disappears while boulders are being reduced to sand grains, reappears (after undergoing chemical alteration) as clay.

Sedimentary rocks formed by deposition on dry land or in fresh waters are known as *continental* in contrast to *marine* (oceanic) deposits. Only a relatively small amount of sediment is deposited on dry land. Wind, ice, and volcanic explosions may mantle the land surface with sediments. A glacier carries with it many tons of rock debris which is left behind when the ice melts. Volcanic ash blown out by mighty explosions may blanket a large area to the leeward of the volcano to a depth of several feet.

Unconsolidated continental deposits, whether made by wind, ice volcanic explosions, or running water, form *transported mantle.* Like residual mantle (Chapter 3), transported mantle covers and obscures the bed rock.

The clastic material that is deposited in river valleys is sediment on its way to the sea, but it has not yet reached that ultimate goal. The character of the sediment in the stream beds depends both upon the character of the rock into which the stream and its tributaries are entrenched and upon the velocity of the water in the stream. The bed of a mountain torrent may be covered with huge boulders, while silt is the principal deposit in the flood plain of a sluggish prairie stream. In most areas the valley fill contains several different sizes of material, testifying to different stream velocities in the past.

Other depositories for clastic sediment are lakes and oceans. Streams entering a lake lose velocity almost immediately and drop their sediment. The floor of the lake becomes covered with material which may eventually accumulate in sufficient thickness to form beds of sedimentary rock. If a lake is not drained through downcutting of the outlet stream, it may be destroyed by becoming filled with sediment.

The great depository for clastic sediment is the ocean. All of our great river systems empty into the ocean, and the volume of sediment which they carry is stupendous. As the river waters enter and mingle with the ocean waters, the velocity is checked, the material which was dragged comes to rest, and the suspended particles begin to settle down onto the sea floor. The deposit which is formed at the very mouth of a river is called a *delta* (Chapter 8).

By no means all of the clastic material brought into the ocean by the rivers finds a final resting place in deltaic deposits. Currents moving parallel to the shore pick up some of this sediment and carry it for many miles along the shore line, where it mingles with the clastic sediment produced by the waves pounding on the rock at the water's edge. The finest suspended material brought to the ocean by the rivers (such as clay) travels farther seaward before dropping onto the ocean floor. However, very little clastic material gets beyond the continental shelves into the ocean basins. Exceptions occur where the ocean basin lies immediately offshore, as along the Pacific coast of South America.

During the geologic past the oceans overflowed the continents to far beyond the present shorelines, many times. The sediment washed off the remaining land areas came to rest on the floors of these much enlarged continental shelves. Here is the reason why three-fourths of the present land surface is covered with sedimentary rock. The area not covered with sedimentary rock today was no doubt also submerged during various past geologic periods, but the sediments deposited have subsequently been removed by processes of erosion or have been buried beneath younger rocks of igneous origin.

Most of the dissolved material which is carried to the ocean remains in solution. Many different compounds, including calcium carbonate (which in solid form is the mineral calcite), sodium chloride (salt), calcium sulphate (anhydrite or gypsum), iron compounds, and even silica, occur in ocean water. In addition there are many rare salts, including the economically important potassium compounds. *Precipitation* of these compounds takes place wherever a body of water containing them in solution evaporates. Our greatest deposits of salt and allied minerals have been formed by the evaporation of land-locked bodies of ocean water. For the formation of deposits of salt several hundred feet thick, similar to those occurring in parts of the United States, a bar or similar low barrier must lie between the evaporating sea and the open ocean. Occasional excessively high tides sweep over the barrier and bring in a fresh supply of salt-containing water, of which the water alone evaporates.

Gypsum or anhydrite are practically universal associates of salt, because calcium sulphate is an abundant constituent of ocean brines.

The Stassfurt region of Germany and the Texas-New Mexico boundary district not only contain deposits of salt, gypsum, and anhydrite, but also a number of rare and very valuable potash salts. Because the potassium compounds are very soluble, they will be precipitated only after the brine has been almost completely evaporated.

The evaporation of lake and sea waters may also cause the precipitation of calcium carbonate, making limestone deposits, and iron oxide, forming beds of sedimentary iron ore.

A relatively insignificant amount of sedimentary rock is formed on land through precipitation of compounds dissolved in surface-reaching ground waters. Some hot spring waters contain large quantities of calcium carbonate and silica which are precipitated through the cooling and evaporation which takes place at the surface.

The third and last group of sediments includes those that are of organic origin. Both animals and plants may form sediments. In some cases the entire organism becomes rock material, in others only the shell which enclosed the animal or plant is preserved. Almost all animals build either an internal bony skeleton or a hard external shell. The shellfish remove calcium carbonate or, more rarely, calcium phosphate from the surrounding sea water and construct a shell which functions as a dwelling in which the animal lives. Some animals, such as the corals, are *colonial,* and live in large groups. Instead of constructing isolated shell homes, these animals build enormous apartment houses in which many thousands of individuals live. When a colonial animal dies, the scavengers of the sea devour the soft body part, but the shell remains intact. Subsequent generations build their apartments on top of the abandoned homes of their predecessors, so that eventually a *reef* will form. This is one way in which limestones are made. The non-colonial marine shellfish, such as the clams and snails, live in such abundance in some places that, as time goes on, their abandoned shells accumulate in deposits of sufficient size to form another type of limestone. There are still other marine shell-building animals which are microscopic in size, but whose shells may nevertheless accumulate in thick deposits which later become consolidated into chalky limestone. Most of our shell limestones are of marine origin, although fresh-water organisms that secrete calcium carbonate are not unknown. The marine shellfish live in relatively shallow water. Even the coral reefs which form islands in the Atlantic and Pacific oceans surrounded by deep ocean basins grew in shallow water. The reefs cap the tops of volcanic peaks that do not quite reach the water's surface.

The bones and teeth of fish contain large amounts of phosphorus, and, in addition, a few shellfish (which were more abundant in the geologic past than at present) build their shells of phosphatic material. The accumulation of these phosphatic compounds is one step in the formation of phosphate rock.

Plant remains may accumulate into sufficiently thick deposits to form beds of coal. This accumulation takes place either in fresh-water lakes or in coastal swamps in which the infiltration of sea water is insufficient to make the swamp water more than slightly saline. The clay and silt that are washed into the lake or swamp in which the coal-making materials are accumulating form ash when the coal is burned. If enough clay or silt is washed in, carbonaceous shale instead of coal is produced.

One of the lowest types of plants, the *diatom,* removes silica from the water in which it grows, to form a shell or *test.* Although these tests are microscopic in size, they may accumulate into deposits of *diatomaceous* earth many feet thick. Some varieties of diatoms live in fresh water; others live in the ocean.

Lithifaction. The final stage in the formation of sedimentary rock is lithifaction. By this process loose, incoherent sediment is consolidated into solid rock. Lithifaction may be produced by *compaction, cementation, crystallization,* or by a combination of these processes.

The sediment which is deposited on the sea floor becomes covered with newer (younger) sediment, so that it may eventually be buried to a depth of hundreds of feet. The weight of the overlying material causes the sediment to compact, and a large amount of the water which was present between the particles is squeezed out. The individual grains are pressed together to such an extent that interlocking takes place, and the material ceases to be incoherent. Compaction can be illustrated by squeezing a mass of wet soil in the hand.

Cementation is a very effective method of rock consolidation. Compounds in solution in the water between the sedimentary grains precipitate and act as a cement, binding the grains together. The commonest cements are calcium carbonate (calcite) and hydrous iron oxide (limonite). A very strong but less common cementing medium is silica (quartz). A rock which is tightly cemented with silica has a toughness equal to that of fresh igneous rock. Limonite-

and calcite-cemented rocks are more readily broken up, but they still have greater coherence than uncemented rock.

Precipitated sediment is consolidated by crystallization. The compounds which come out of solution in a body of water and slowly settle to the bottom are in a finely divided state. Subsequently these minerals crystallize into an interlocking aggregate. The result is a dense, compact rock.

FEATURES OF SEDIMENTARY ROCKS

Stratification. Because of the way in which sedimentary rocks are formed, they exhibit a number of features that distinguish them from igneous and metamorphic rocks. In the first place, almost all sedimentary rocks are *stratified* (occur in layers) (Fig. 99). This layering is caused by the sorting effect of the medium in which the sediment was deposited and by differences in type of sediment. At one time and at one place the current conditions are uniform, so that sediments of a certain size (or weight) only will be deposited. The coarser (heavier) material is not carried so far, and the finer material will be carried by. Later, when a change in water velocity occurs at this point, a thin layer of coarser or finer material will be deposited above the earlier material. Such velocity changes are taking place constantly, so bands of material of different size overlie each other. Furthermore, the streams entering the body of water in which deposition is taking place may bring in

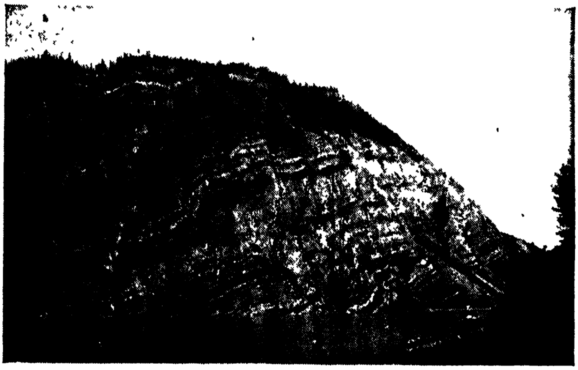

Fig. 99. Disturbed rock strata. Calico Bluff, Yukon River, Alaska. *By J. B. Mertie, Jr. Courtesy Geological Survey, U. S. Department of the Interior.*

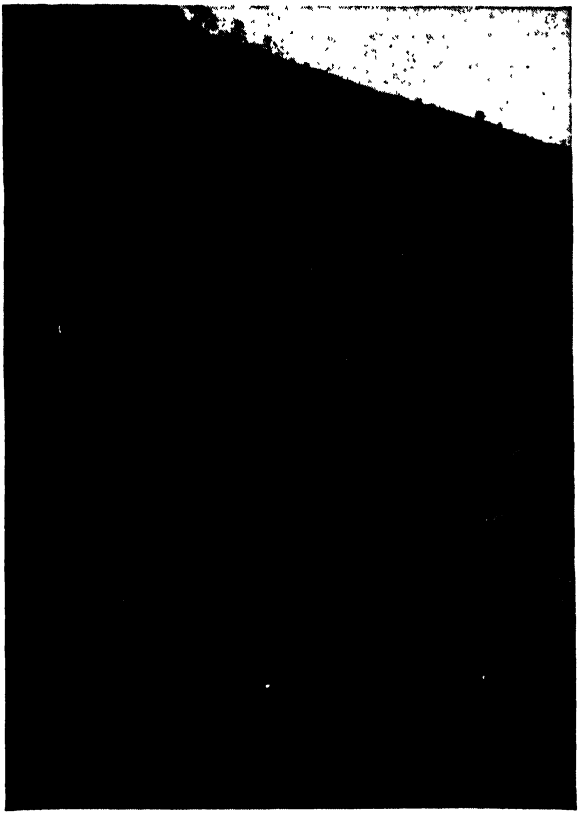

Fig. 100. Weathered surface of cross-bedded sandstone. Zion National Park. *By George A. Grant. Courtesy National Park Service, U. S. Department of the Interior.*

different types of material at different times. During some seasons of the year finely divided plant material mixed with silt will be brought in by the streams and deposited as a dark layer on the floor. Torrential rains may cause a temporary influx of coarse, light-colored mineral grains which will overlie the darker sediment. Thus color banding is produced.

Wind, running water, and ocean currents all have ability to sort sediment so that stratification will result. Moving ice (glaciers) is exceptional in that it does not sort the sediment which it carries. In consequence, glacial drift is unstratified. However, much of our glacial material has been reworked by streams passing through the drift sheets, and this secondary activity has produced stratification.

Stratification is evident in sedimentary rocks in varying degrees of magnitude. In many places very thin *laminae* (layers), only a fraction of an inch in thickness, are visible. These in turn group together to form a *bed,* such as a bed of sandstone. A *formation* is either a single thick bed of one kind of rock or a series of beds of different kinds of rock, the outcrop of which can be mapped by the geologist.

Rock stratification is a great aid to the geologist in his interpretation of earth history. He knows that the deeper layers are older than the higher layers, because they must have been deposited first. Geologic history of the earth and the evolutionary development of our plant and animal life have been traced by following this fundamental law of stratigraphy: *Overlying strata are younger in age than underlying strata.* An exception occurs where rocks have been overturned. Geologists have determined the relative age of the rocks in all accessible parts of the world.

Cross-bedding. A feature shown by some sedimentary rocks is *cross-bedding* (Fig. 100). The individual beds or laminae do not actually cross, as the term implies, but may appear to until examined closely. Cross-bedding is a common phenomenon in windblown deposits. The sand is deposited on the leeward side of the dune in layers which dip in the direction of wind movement. A slight shift in the direction of the wind will change the direction of dip of the sand layers. In that way alternate layers of sand become "cross-bedded." The same thing takes place in river channels where changes in the direction of current flow cause adjacent laminae to dip in different directions.

Deltaic deposits (Fig. 101) illustrate cross-bedding on a grand scale. Sediment is dropped at three different places on the delta: (1) on the nearly flat top, (2) on the seaward or lakeward slope at the outward end of the main delta, and (3) on the sea or lake floor out beyond the delta proper. The sediment deposited in the first and third places will be nearly horizontal, while that deposited on the outward-moving "nose" of the delta will be inclined. In consequence a cut through a relatively undisturbed delta will show early flat-lying layers at the bottom (*bottomset* beds) which were deposited before the main delta had moved to that point; inclined layers above (*foreset* beds), which were deposited on the outward edge of the main delta when it occupied that position; and flat-lying sediments on top (*topset* beds) which were deposited after the "nose" of the delta had moved on.

Other features of sedimentary rocks. Sedimentary rocks may have *ripple marks* (Figs. 102 and 103) and *mud cracks.* The former are distinctive corrugations made by local wave-created currents working on the surface of unconsolidated sediment covered by shallow water. Where ripple marks are preserved they occur on the tops of rock strata. Mud cracks occur where sediment is exposed to the air sufficiently long to dry out and contract into many-sided blocks. Later, sediment of a different type may be deposited in the cracks and across the top so that the mud-crack structure is preserved and becomes visible when the rocks are reexposed by erosion.

Rounded, tightly cemented nodules of mineral matter occurring in sedimentary rocks are known as *concretions.* Those formed by ground water precipitation were described in Chapter 4. It is also believed that concretions can be formed on the sea floor at the time that the surrounding sediment is being deposited. Such *contempo-*

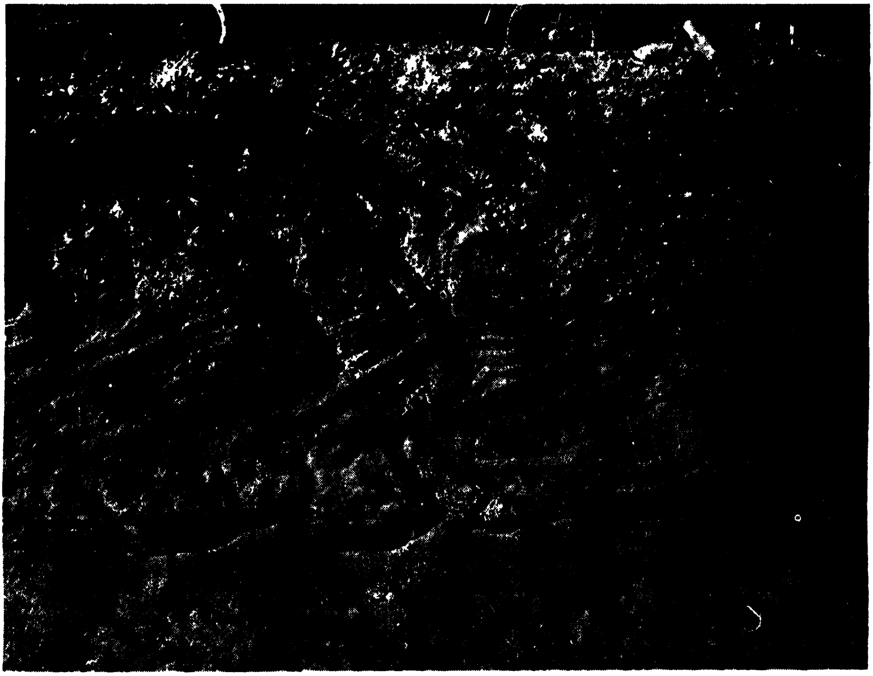

Fig. 101. Topset, foreset, and bottomset beds which were deposited in delta in temporary lake bordering continental ice sheet. University of Michigan campus, Ann Arbor. *By R. C. Hussey.*

raneous concretions occur over wide distances, and may be used for purposes of identification and correlation of the containing formation. In some instances the concretions are widely spaced; in others they are so close together that they merge to form a continuous bed. The shapes may be spherical, elliptical, discoidal, or irregular. Sizes vary from less than one inch across to several feet. Silica, in the form of chalcedony (chert or flint) is a very common concretion-making compound. Calcium carbonate (calcite), iron sulphide (pyrite or marcasite), and other substances also occur in concretions.

A very valuable criterion of the identity and age of sedimentary rocks is the presence of *fossils,* which give evidence of the former existence of plants or animals. In some instances actual remains of the organisms are found, such as an animal's tooth, the shell of a clam, or the test of a diatom. In other instances the organism has been *petrified,* which means that the organic material has been completely replaced by mineral matter, without necessarily destroying its original shape and markings. Petrified wood is formed through the particle-by-particle replacement of woody material by silica. Some fossils are merely molds or casts of organisms. Molds are formed where mud or other sediment has completely enfolded an organism (or has

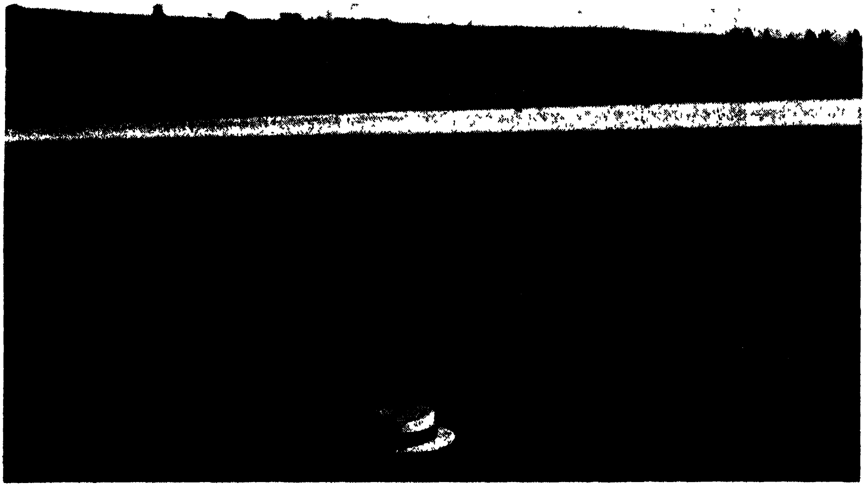

Fig. 102. Current ripple marks left by ebbing tide in unconsolidated sediment. Windsor, Nova Scotia. *Courtesy Canadian Department of Mines and Resources.*

filled an interior cavity) after which the organism has been dissolved away. A cast is formed by sediment filling in an exterior mold. The non-organic material in molds and casts may preserve remarkably well the shape of the original organism. Preserved footprints, tracks, trails, and burrows are likewise considered to be fossils.

The *color* of sedimentary rocks is a blend of the colors present in the mineral grains and in the material lying between the grains. The most resistant of the common minerals composing the crust of the earth is quartz, so this mineral is common in sedimentary rocks. Clay minerals are also abundant. Calcite is the essential ingredient of limestone. All of these minerals tend to be light in color, so sedimentary rocks composed entirely of these minerals are white or gray.

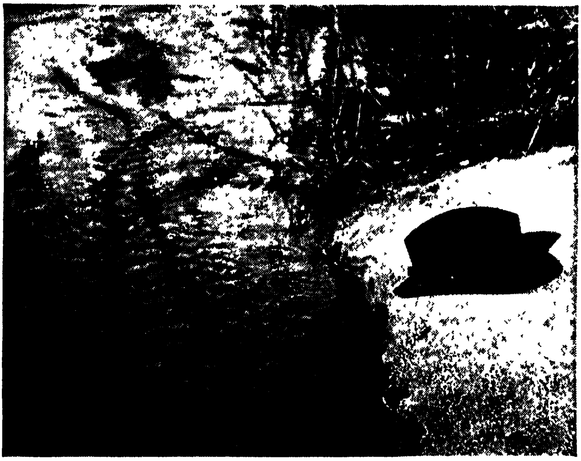

Fig. 103. Ripple marks being made by flowing stream water. *Courtesy Canadian Department of Mines and Resources.*

However, carbonaceous matter is black, and where such material was deposited with the other sediment the resulting rock is darker in shade. Sandstones, shales, and limestones may vary in color from white through various shades of gray to black, depending upon the amount of carbonaceous matter present. Red tints are also found in sedimentary rocks. In most cases these colors are due to the presence of iron minerals which were either deposited with the other sediment or were subsequently introduced by ground waters which precipitated them as cement between the grains. Hematite (iron oxide) produces red colors, and limonite (hydrous iron oxide) yellows and browns. These are powerful coloring agents, and a relatively small quantity is sufficient to color a large amount of rock. The southwestern United States contains many cubic miles of "red beds," hematite-colored sedimentary rocks which contribute much to the beauty of that region. Several national parks and monuments, such as Bryce and Zion, are places in which erosion has exposed a thick series of red beds. Where the hematite is less abundantly disseminated through inherently white rock, the resulting shade is pink. Iron minerals scattered through rock may alter to limonite upon exposure to the atmosphere; many light colored rocks, especially limestones and sandstones, are yellow or buff at the outcrop for this reason.

VARIETIES OF SEDIMENTARY ROCK

Classification. Sedimentary rocks are classified according to the nature of the original sediment. The largest group is the clastic, which includes all rock composed of fragmental material. The clastic rocks are subdivided on a basis of size or *texture* of the component grains; further division is made in the case of coarse clastics on the degree of rounding shown by the individual fragments. Subvarieties, not considered in this book, are based on the mineral content of the clastic grains.

The second group of sedimentary rocks includes the chemical deposits, which consist of compounds precipitated from aqueous solutions. The evaporation of mineralized water, such as found in hot springs, salt lakes, and bodies of sea water separated from the ocean through one cause or another results in the formation of sedimentary rocks of this type. The name of the rock is dependent upon the chemical composition.

CLASSIFICATION OF SEDIMENTARY ROCKS

I. Clastic Deposits

TEXTURE	UNCONSOLIDATED	CONSOLIDATED
Fine	*Clay, silt*	*Shale, siltstone*
Intermediate	*Sand*	*Sandstone, quartzite*
Coarse	*Boulders, cobbles, gravel*	*Conglomerate, quartzitic conglomerate*
	Angular clastics	*Breccia*
Mixed	*Till*	*Tillite*

Organic deposits constitute the last group. In some cases the rocks in this group consist of accumulated organic matter (which may, however, have passed through a long and involved series of chemical changes since deposition), in others the rocks are composed, not of organic material, but of mineral compounds which were extracted from water by organisms. This group is of great economic importance because it contains, or is the source of, the mineral fuels: coal, petroleum, and natural gas.

II. Chemical (Precipitated) Deposits

CHEMICAL COMPOUND	ROCK NAME
Calcium carbonate	*Limestone, tufa*
Calcium magnesium carbonate	*Dolomite*
Calcium sulphate	*Gypsum, anhydrite*
Sodium chloride	*Salt*
Silicon dioxide (silica)	*Chert, flint* *Siliceous sinter*
Iron oxide	*Sedimentary iron ore*

III. Organic Deposits

MATERIAL	ROCK NAME
Diatoms	*Diatomaceous earth*
Shells	*Limestone*
Phosphatic organic material	*Phosphate rock*
Plants	*Coal*

It is *not* intended by this classification to set up fixed pigeonholes in which every sedimentary rock can be placed. Complete *gradation* exists between many of the rocks shown in the table; furthermore, different types of sediment may be deposited together, resulting in a mixed rock. For example, the line of demarcation between fine gravel and coarse sand is an arbitrary one; a rock composed of such material may be called either a fine conglomerate or a coarse sandstone. In the other direction sand grades into silt, so that there is no natural boundary between sandstones and shales. Also silt or clay particles may be deposited between grains of sand, so that there is every gradation possible from sandstone through shaly sandstone and sandy shale to shale. The sea floor on which organic material is accumulating may receive clastic sediment settling from the waters above; in consequence, the sedimentary rocks in the crust of the earth include sandy and shaly limestones, and every gradation from coal through shaly coal and carbonaceous shale to shale. The evaporating body of water in which salt is being precipitated may receive silt or clay from inflowing streams so that a shaly salt or a salty shale will result. Many other examples of gradations and mixtures in sedimentary rocks could be cited.

Shale and siltstone. The finest clastic particles consist of either clay minerals, which are formed by the decomposition of feldspar, or of silt, which is made up of finely ground grains of primary minerals, mainly quartz. Because these particles are very small (under 1/250 inch in diameter) they are transported mainly in suspension and will settle down onto the floor of lake or sea only where the water is very quiet; in other words, out beyond the zone of breaking waves and strong shore currents. Clays and silts are consolidated mainly by the pressure exerted by younger, overlying sediments. A large volume of water is squeezed out and the individual particles are pressed together into an interlocking aggregate. The resulting rock is relatively soft but very compact.

The fact that shales and siltstones constitute over four-fifths of the sedimentary rocks shows that most clastic material is broken down by chemical and physical processes to a very fine size before being deposited in its final resting place. Most shales and siltstones are marine, but there are some very thick formations which were deposited entirely in fresh water. This information is obtained by a study of the fossils (mainly the remains of very small organisms) which may be present in the shale or siltstone.

Fineness of grains and softness are two of several characteristics by means of which shales and siltstones can be identified. These rocks tend to split easily along bedding planes. The bedding planes are close together; in some shales the individual layers or beds are no thicker than a sheet of paper. In many cases adjacent layers in a shale are differently colored, due to slightly different conditions at the time of deposition. It is believed that some color banding, especially where light layers alternate with dark, marks differences between summer and winter deposition; a pair of such layers therefore represents a year, and the length of time consumed in depositing a shale formation of this type can be ascertained by counting the total number of color pairs.

Commonest shale and siltstone colors are gray and black. A pure clay shale is light gray; the presence of organic material darkens the shale so that the strongly carbonaceous shales are as black as coal. Shales containing ferric iron minerals are red; the thick "red bed" deposits of the southwestern United States consist of both red shales and sandstones. Other colors less commonly seen in shales are pink, maroon, purple, yellow, brown, and green.

Most shales and siltstones are *friable,* crumbling readily when rubbed between the fingers. The weathering of a shale consists mainly of soaking up water, which produces swelling and reversion to the original clay. Because of their fine grains, softness, friability, and ready disintegration by weathering, shales are among the most easily eroded of rocks. Under conditions of semi-aridity, thick shale or siltstone formations directly underlying the surface are carved into "badlands" by running water. Bryce Canyon, a National Park in Utah, is a badlands in a multicolored shale formation. Where these rocks are interbedded with more resistant rocks, such as sandstones or limestones, erosion will produce relatively gentle slopes over the area of shale outcrop. In humid climates such slopes are covered with vegetation; therefore, outcrops of shale are ordinarily seen much less frequently than outcrops of other sedimentary rocks which are much less abundant.

The percentage of shale utilized industrially is insignificant compared to the total volume available. However, clays, occurring either in clay shales or in deposits which have never been compressed into shale, are of considerable industrial importance because they can be shaped and heated ("fired" or "burned") to produce hard and durable objects. The most characteristic property of clay is *plasticity,* which is the ability to be molded without rupture when wet, and to retain the molded form when dry. The color of burned clay varies from white to red and even black, with various intermediate shades such as cream, yellow, and buff.

The manufacture of clay products is known as the *ceramic* industry. Clay products may be classified into refractory (bricks, crucibles, and retorts), structural (brick, tile, and terra cotta), domestic (vitrified brick, sinks, sewer pipes, chinaware, and pottery), and electrical (insulators). In volume, brick and tile exceed the other ceramic products, but in value pottery heads the list because of the cost of the high quality clay used and the skilled artisanship necessary to produce marketable ware. Unburned clay is used in the manufacture of Portland cement and as a filler in paper and paints.

Oil shale is a carbonaceous shale which will yield oil upon distillation. Since oil shales contain no oil, however, squeezing, or soaking in solvents, will not produce results. The oil has to be generated from the carbonaceous matter by heat. Most oil shales are of the fresh-water type and the organic material present consists of plant remains, especially spores and pollen. Oil shales might logically be described as high-ash cannel (spore) coals. The first step in exploiting an oil shale deposit is to mine the shale. Then the shale is placed in large retorts and heated. The gases given off are condensed and an oil analogous to crude oil produced. One ton of shale may yield twenty or more gallons. The retort oil is then refined and the usual petroleum products, though in different proportions, are obtained.

Scotland and France have had a small oil shale industry for many years. The United States contains an enormous reserve of oil shale, especially in parts of Colorado and adjacent states which are underlain by the thick Green River shale. It has been calculated that more oil is tied up in these oil-shale deposits than has been so far produced in the United States. About 1920, when very few new fields were being discovered and a petroleum shortage was in prospect, considerable experimentation was carried on with domestic oil shale. However, many new oil fields were subsequently discovered, and inasmuch as oil shale cannot be exploited profitably in this country, with crude oil at or near its present price, oil-shale activity became dormant. But the petroleum reserves of the world, although now known to be enormous, will not last forever, and the oil-shale deposits of this and other countries constitute an important reserve upon which future generations will be able to draw.

Sandstone. As the name implies, sandstones are composed of sand grains. These grains consist of the most indestructible minerals in the source rock, which are carried by water or wind to a final resting place. In the process, the grains may become rounded through rubbing.

The greatest volume of sand is deposited in the ocean; it is both brought in by the rivers entering the sea and obtained by wave erosion along the coast line. In a similar manner, sand may be deposited on the beaches and floors of interior seas and lakes. Some sand deposits are obviously of deltaic origin; such deposits can be recognized by the steeply dipping *foreset beds* (Fig. 104) which mark successive outer edges of the delta. The beds of many rivers contain sand; one great source of industrial sand is streams from which the sand is dredged or pumped. In rare instances stream sands have been covered by younger sediments and preserved, forming so-called "shoestring" sandstone bodies which in a few parts of the United

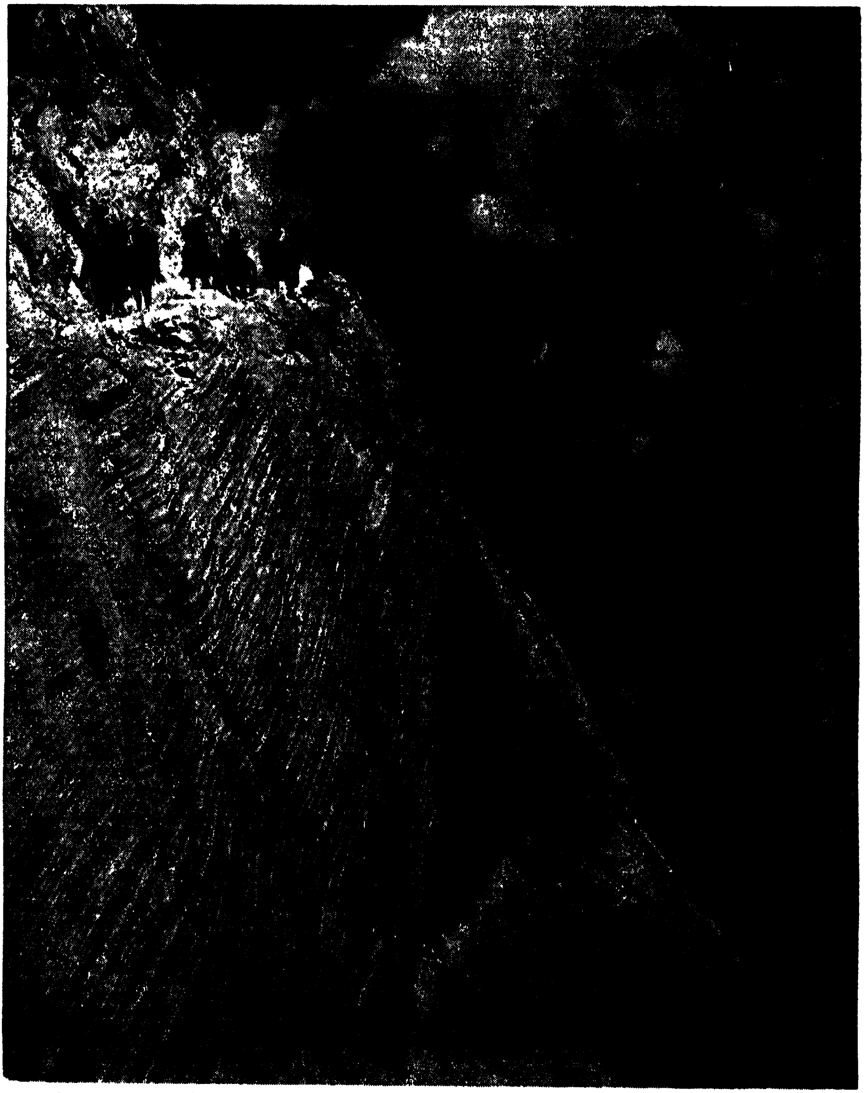

Fig. 104. Sandstone containing foreset beds. Zion Canyon, Utah. *Courtesy Union Pacific Railroad.*

States contain commercial supplies of oil. Windblown sand also has accumulated in the past in deposits which have been preserved.

Sandstone beds are in most cases interbedded with shale (Fig. 105). Obviously, the conditions under which deposition took place in the past were constantly shifting. A slight depression of the shore line might have made a spot that was formerly being covered with sand sufficiently deep or far offshore so that the waters were quiet, and clay was deposited over the sand. An elevation of the shoreline to somewhere near its original position might then have restored the previous conditions so that sand would be deposited again, this time above the clay. Or the streams might have become more active because of greater rainfall or tilting of the surface so that the gradient would be increased, in which case the sand would be carried out and deposited over areas which were heretofore receiving only clay or silt. The many alternations between shale, sandstone, and other sedimentary rocks in the earth's crust attest to an almost endless shifting of conditions in the geologic past. No doubt these same shifts are taking place today, but the rate of change is so slow that it makes little impression upon us.

Sands are converted into sandstone mainly by cementation of the grains. Because of their shape, sand grains cannot be packed closely.

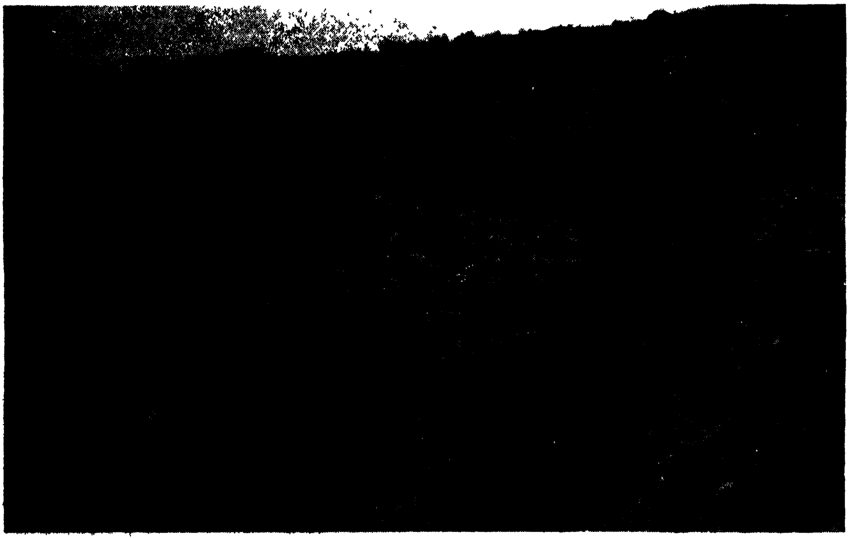

Fig. 105. Fluted cliff face of sandstone with interbedded shale. Jutting layers are more resistant sandstone beds; soft shales lie back of the horizontal grooves. Castle Rock, near Florence, Colorado. ***By R. C. Hussey.***

Although every grain may be wedged tightly in place, the rounded surfaces cause open spaces to remain between the grains. In fact about 40 per cent of the volume occupied by a sand consists of interstitial (between-the-grains) openings, which are so interconnected that air, gases, or liquids can flow fairly freely through them. With but few exceptions these pore spaces are filled with water from the time a sand is first deposited. Minerals in solution in the water may precipitate and act as a cement between the grains. Rarely, however, is this cementation at all complete, so most sandstones still have a porosity of from 15 to 35 per cent of the total volume of the rock.

The commonest substance cementing sandstones is calcium carbonate, the same compound which, when fairly pure, makes a limestone. Hydrous iron oxide (limonite) is another common cementing medium. Sandstones cemented with limonite are yellow, buff, or brown in color. Some sandstones are cemented by silica, the same compound (quartz) as most of the grains in the average sandstone. Silica-cemented sandstones are very strong; the cement is just as hard as the grains themselves, so that these rocks fracture through the grains instead of around them, as is the case with other cements. Quartz sand grains completely bound together by silica make one type of *quartzite,* an exceptionally tough rock. Many of the older sandstones in the earth's crust and, here and there, younger sandstones have been cemented into quartzites by precipitation of silica cement from ground waters. Iron carbonate or oxide may also be cementing material. Cementation changes a loose aggregate of sand into a compact rock. A loosely cemented sandstone may be friable; one tightly cemented is not.

About one-eighth of the sedimentary rock in the earth's crust is sandstone. However, sandstones are more resistant to erosion than the much commoner shale, and are therefore more prominent topographically (Fig. 50). In many places they form the cap rock for hogbacks and mesas, features which were described in Chapter 5. The resistance of sandstone to erosion causes steep slopes to be formed where nature carves into or through beds of this material. The rock forming the sheer walls of Zion Canyon in Utah, Canyon de Chelly, Arizona, and many canyons elsewhere is sandstone.

Sandstones are easily identified because they consist of visible grains of sand. These grains are always partly rounded and may be almost spherical. Quartz, due to its abundance in granite, and its resistance to physical disintegration and chemical decomposition, is by far the most common mineral in sandstones. Where feldspars and other less stable minerals are present, the assumption is that either the climate was excessively dry at the time of deposition, slowing down decomposition, or else the sand was carried but a short distance from its source. Additional evidence concerning the distance and type of transportation can be found in the degree to which the individual grains, originally angular, have been rounded. The farther a grain has been transported, the more rounded it will be. Scattered among the grains in a sandstone may also be heavier minerals, such as metallic compounds, which are as stable as quartz but less abundant because they were relatively scarce in the source rock. The separation and identification of these minerals supply evidence as to the type of rock from which the sediment was derived.

Individual beds of sandstone are on the average much thicker than those of shale; some single beds are many feet thick. Thin beds are not unknown, however, and, where the beds are differently colored, a banded sandstone is the result. Sandstones may split along bedding planes, but the separation is not as easy as it is in the case of shale. Most sandstones are white or grey, but a limonite cement produces a yellow, buff, or brown stone, and hematite makes a red sandstone. Other colors are uncommon.

A property of sandstone which is not readily discernible but which plays an important role in the storage of ground water, petroleum, and natural gas, is porosity. By means of the interconnecting pore spaces, gases and fluids can move through, and be stored in, sandstone.

The weathering of sandstone is accomplished mainly by the solution and removal of the cement that holds the grains together. Calcareous cement is especially susceptible to solution by water at and near the surface. With the removal of the cement the sandstone again becomes a loose aggregate of sand and can be carried away easily by running water and wind. The sand grains themselves, because they consist mainly of quartz, are not very susceptible to weathering agents.

Throughout historic time sandstone has been used as building stone. A few decades ago a brown sandstone occurring among the rocks of the North Atlantic coastal region was very popular, and many "brownstone" houses were built in the cities of that area. In more recent years the fad has turned to white Indiana limestone as a building stone, and the quarrying of sandstone has declined. However, there still are many quarries producing sandstone for local consumption.

Grindstones are made of sandstone which is neither too fine nor too coarse, and neither too tightly nor too loosely cemented. Most of the grindstones produced in the United States come from a single sandstone formation which outcrops in Ohio.

Many of the major groundwater reservoirs are sandstones. The northern Great Plains area obtains most of its water from a widespread sandstone formation known as the Dakota. Likewise, sandstone is an extremely important reservoir rock for oil and gas. In drillers' terminology, any oil- or gas-producing bed, whether it be a sandstone, limestone, or dolomite, is called a "sand."

Coarse clastics. One variety, termed *conglomerate* (Fig. 106), is made up of waterworn boulders, cobbles, and pebbles. with

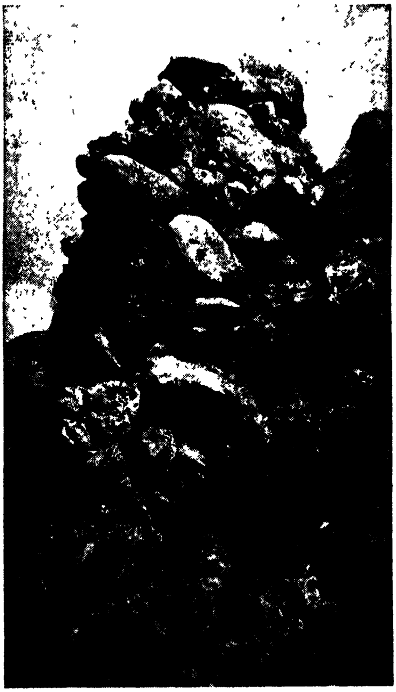

Fig. 106. Exceptionally coarse conglomerate. Hammer in center gives scale. Malm Gulch, Custer County, Colorado. *By C. P. Ross. Courtesy Geological Survey, U. S. Department of the Interior.*

sand ordinarily filling the interstitial spaces between the coarser sediments. These materials accumulate along the shoreward edges of beaches, and in the beds of fast moving streams. They become cemented by the same compounds that cause grains of sand to adhere in a sandstone. Where silica is the cementing medium, the rock is called a *quartzitic conglomerate.* Conglomerates are composed of worn fragments of rock, and quartz is only one of a number of minerals which may be present in this rock. The individual boulders are readily discernible, so recognition of a conglomerate, or "puddingstone," as it is often called, is easy. Conglomerates are relatively scarce.

A *breccia* is composed of angular rock fragments cemented together (Figs. 85 and 98). Coarse material ejected from a volcano, or talus which accumulates at the base of a cliff, may be cemented to form breccia. The heterogeneous collection of sub-angular and unsorted rock fragments transported and deposited by a glacier is till; upon cementation the rock becomes a *tillite.* The presence of tillites among sedimentary rocks gives evidence of ancient glacial periods.

Limestone. Limestone is listed twice on the table given on page 225 because it can be formed both through the precipitation of calcium carbonate from water, and through the removal of this compound by organisms, mainly shellfish. As a matter of fact, many limestones are formed by a combination of these processes. Most, but not all, limestones were deposited in salt water.

Calcium compounds are fairly common products of the decomposition of such minerals as the feldspars. Carbon dioxide is produced both by volcanic activity and by organisms. Consequently, the rivers emptying into the oceans carry the elements necessary to make calcium carbonate, a compound which is relatively insoluble and so is readily precipitated. The presence of even minute amounts of calcium carbonate dissolved in water is all that is necessary for the growth of various types of animals, and some plants, which remove it from the surrounding water. A few limestone formations are quite obviously ancient reefs, but most limestones of organic origin are formed through the accumulation on the sea floor of countless millions of individual shells.

The limestones lying at and near the earth's surface are themselves a source of calcium carbonate. so some limestone building may be an endless cycle with older calcareous rocks supplying the material necessary for the formation of younger limestones.

Calcium carbonate accumulates on the sea floor as unconsolidated *calcareous ooze* or, in the case of organic deposits, as an incoherent collection of shells. Lithifaction is accomplished in part by pressure, which squeezes out the water, but mainly by crystallization of the calcium carbonate into an interlocking aggregate of calcite crystals, producing an exceedingly compact rock; most limestones are not friable in the least.

Limestones (and dolomites) compose about 6 per cent of the sedimentary rocks in the earth's crust. These rocks are therefore much less abundant than shale, and only about half as common as sandstone. Nevertheless, limestones are fairly widespread and, like sandstone, are more resistant to erosion than the associated shale, so that good exposures are fairly common (Fig. 107).

The sole essential mineral in limestone is calcite, but in many cases the individual crystals of this mineral are too small to be recognized. Limestones are easily identified through the bubbling or effervescence that takes place when the surface is touched with a drop of dilute acid. Many limestones contain scattered shells of

Fig. 107. Limestone, with relatively thin interbedded softer shales, exposed in creek valley in northeastern Kansas. *By Oren Bingham. Courtesy Kansas Geological Survey.*

clams, snails, and other animals. Because of its mineral composition, limestone is a rather soft rock, scratching readily under the point of a knife blade.

Common limestone is white or gray in color. Where hydrous iron oxide (limonite) is present, the rock is yellow, buff, or brown. Some limestones are black, caused in most cases by the presence of organic material. *Chalk* (Fig. 108) is the name applied to a dense, excessively fine-grained, light-colored limestone that is composed of the shells of microscopic animals. A limestone made up entirely of visible shells and shell fragments is known as a *coquina.*

As well as surface waters, many hot spring waters contain calcium carbonate in solution, which may be precipitated at the surface through cooling and evaporation. The light and porous rock which results is called *tufa* or *travertine.* Tufa deposits are found around present-day hot springs and geysers, and some limestone formations are believed to have been tufa deposits originally.

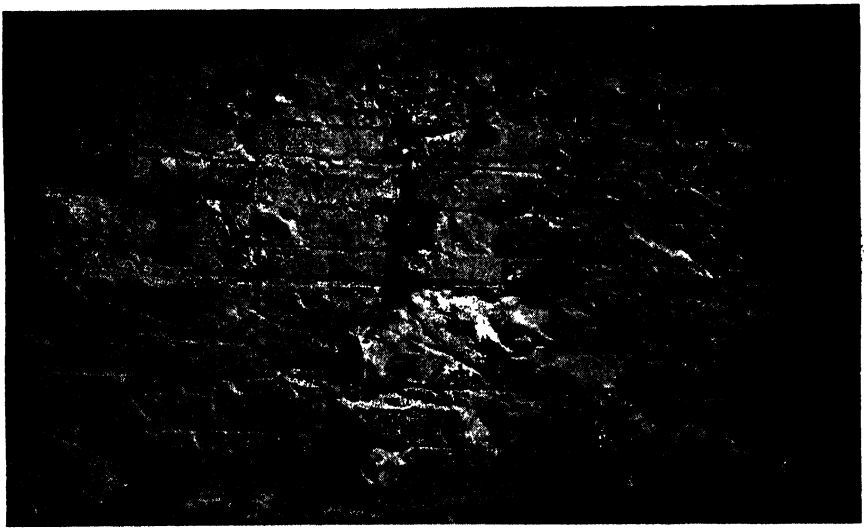

Fig. 108. Chalk in thick massive layers. Man in center gives scale. Smith County, Kansas. *By Kenneth K. Landes.*

The weathering of limestones is largely a leaching process. Although practically insoluble in pure water, limestone is readily soluble in water containing carbon dioxide, a compound that is fairly prevalent in surface and near-surface waters. For this reason limestones at the outcrop tend to develop a pitted appearance, and limestones beneath the surface may be made cavernous through the activity of ground water. A continuation of these processes results eventually in the complete removal of a limestone formation.

Limestone is a rock of many uses. Its popularity at the present time as a building stone has already been mentioned. In addition to the great Bedford limestone quarries located in Indiana, which supply white dimension stone for building construction over a large area, there are many smaller quarries that supply a local market. Actually only a relatively small part of limestone quarried is used as dimension stone. Most of it is crushed and used in concrete aggregate, as a road surfacing material, and in the manufacture of lime and cements. It is used also as a furnace flux in metallurgical plants and as agricultural limestone, which is spread over the surface of soils deficient in calcium.

One valuable quality of limestone is its behavior upon heating; high temperatures cause carbon dioxide (a gas) to be driven off, leaving calcium oxide (lime or quicklime). Lime has a high affinity for water, and when water is added it slakes (combines with the water) with evolution of heat to form hydrated lime. Its principal use is to form mortar and plaster with the addition of sand.

Natural cement is made from a shaly limestone in which the impurities run from 15 to 40 per cent. The impure limestone is heated in the same way as in the manufacture of lime, but, instead of making lime, the calcium unites with the impurities to form other compounds. However, the resultant product will slake with the addition of water after it is pulverized. Natural cement manufacture is a minor industry now, but this material was used for many centuries before the discovery of Portland cement.

Portland cement was patented in England in 1824. It was named after its alleged resemblance to a very popular English limestone extensively used for building purposes. Portland differs from natural cement mainly in that the ingredients are first mixed in very definite proportions. If the rocks are pure, three parts of limestone is mixed with one part of clay or shale. This mixture is heated until it clinkers, and then the clinkers are pulverized. The increased use of Portland cement in building construction has caused a decrease in the use of building stone.

Limestones are not as consistently porous as sandstones, yet many limestone beds contain enough openings so that they contain a large volume of water, gas, or oil. These openings may be solution cavities, or they may be interconnecting fractures that cut through this relatively brittle rock. The deeply buried limestones (and dolomites) in the Mid-Continent produce great quantities of oil. The production of limestone wells can be increased by "acidizing," pouring into the well a dilute acid which eats out the limestone and increases the passageways into the well.

Dolomite. Dolomite is a carbonate of both calcium and magnesium. It occurs in sedimentary beds like limestone; in fact most limestones contain some magnesium carbonate, and there is every gradation between limestone, dolomitic limestone, and dolomite. It has been suggested that dolomites have been formed through the replacement of calcium carbonate by waters containing magnesium, this replacement taking place in the calcareous ooze on the sea floor in most instances.

Dolomite is less abundant than limestone but is fairly common, nevertheless, in some regions. It looks like limestone, but it effervesces vigorously in acid only when powdered. Dolomite is used like limestone for building stone, but it cannot be used in cement manufacture. It can, however, be used as a refractory, for it has a higher melting point than limestone. Dead-burned (heated so that the carbon dioxide is driven off) dolomite is used to line open-hearth steel furnaces. An even more valuable refractory is the pure magnesium carbonate, *magnesite,* which is somewhat similar in its occurrence.

Dolomite is also made into compounds used in heat insulation. Deeply buried dolomitic formations in the Mid-Continent are in places sufficiently porous to contain large supplies of petroleum.

Salt and gypsum. Sodium chloride (salt) and calcium sulphate (gypsum) are abundant compounds in sea water and in interior bodies of water that lack outlet. The great beds of salt and gypsum that occur in the earth were formed through the evaporation of sea water that became intermittently separated from the main ocean. Calcium sulphate, which is present in the mineral gypsum, is much less soluble than salt and therefore precipitates before salt during the evaporation of a normal brine. Certain rare salts, including potash compounds, which are even more soluble than sodium chloride, are precipitated only when evaporation continues almost to dryness.

The sodium in salt comes originally from such igneous minerals as feldspar. Chlorine is a gas given off by volcanoes. It is brought to the earth's surface by rain falling through chlorine-laden atmosphere. The union of these two elements produces salt, but because of its great solubility this compound will not be precipitated except through evaporation.

Salt is easily identified by its taste. It occurs in stratified beds in such compact form that in mining it has to be drilled and shot with explosives like any other rock. However, because of its solubility, salt can also be obtained by pumping fresh water down wells and evaporating the resultant brine which is brought back to the surface. Salt crystals are colorless, but most rock salt is white or gray.

Beds of salt do not outcrop except under unusually arid conditions. However, ground waters may penetrate salt deposits and emerge at the surface as salt springs, thus disclosing the presence of hidden salt beds. Salt has also been discovered through drill holes, put down in some cases for salt, but in most cases drilled for water, oil, or gas.

Michigan, Ohio, and New York produce salt from the same formation (Fig. 109). The largest known salt deposit in the world extends from Kansas across western Oklahoma and Texas into east-

Fig. 109. Salt mine. Alternating strata of light and dark salt visible at right and above the figure at left. *Courtesy International Salt Company.*

ern New Mexico. Salt is obtained also from the brine of Great Salt Lake, the Dead Sea, and from ocean water in San Francisco Bay. Louisiana has become an important salt-producing state through the exploitation of salt *plugs* (Fig. 110). These vertical, pipe-like bodies are formed by the upward flowage, under pressure, of salt from deep-seated sedimentary beds. The Stassfurt region in Germany produces not only salt, but also rare and valuable potash compounds.

Salt is the only edible mineral. Essential to the normal diet, it has been sought and treasured throughout historic time. The chief uses of salt are for table use, for butter, for stock, for meatpacking and curing, for pickling, and for adding to the ice used in making ice

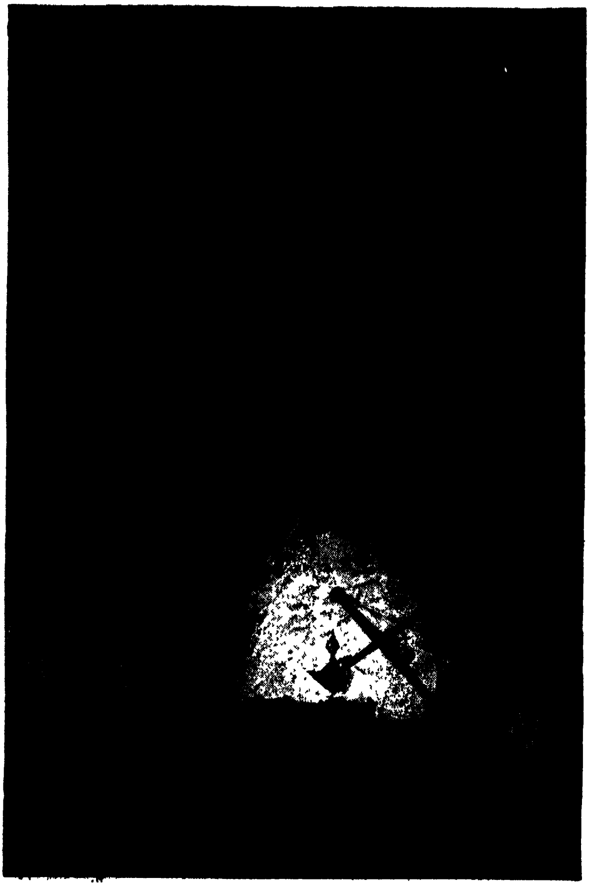

Fig. 110. Large room in salt mine in piercement salt dome or plug. Louisiana. *Courtesy International Salt Company.*

cream. It also is used in large quantity in the manufacture of various chemicals.

It is quite possible that most gypsum (calcium sulphate plus water) was originally precipitated as anhydrite (calcium sulphate without water) which was subsequently hydrated through the addition of ground water. Gypsum deposits are geographically more extensive than salt deposits, because calcium sulphate, less soluble, is precipitated from brine before salt. In some instances the evaporating process was stopped after calcium sulphate had separated out but before salt precipitation began. Gypsum occurs in the same formations previously mentioned as yielding salt and, in addition, in strata in the Rocky Mountain region.

Most rock gypsum is white in color. It is so soft that it can be scratched with the fingernail. Anhydrite is very similar in appearance but is slightly harder. These rocks may be interbedded with layers of salt or shale, because of changes in local environment at the time of deposition.

Some gypsum is used in "raw" form as a retarder in Portland cement, as a fertilizer (gypsum is not in itself a plant food but it often reacts with other substances to produce plant food), as a base in paints and insectides, and as a filler in cotton and paper. A compact, dense variety of gypsum known as alabaster has been used in place of marble by sculptors.

Most gypsum is burned or "calcined." In this process three-fourths of the chemically combined water is driven off, and the resulting product, known as plaster of paris, has the ability to recombine with water and "set" into the shape to which it has been molded. The chief use of plaster of paris is in wall plaster, but it also has many other uses, including plaster board, tile, stucco, surgical casts, and models of many types.

Gypsum may also be burned to complete dehydration to produce a product (Keene's cement) which is likewise used as a plaster.

Sulphur. A natural by-product of gypsum is free sulphur. In a few localities the calcium sulphate in gypsum (or anhydrite) has been reduced by bacterial action so that the bed is partially or completely altered to native sulphur. The only extensive sources of free sulphur for many centuries were such deposits on the island of Sicily. The Sicilian monopoly was broken in 1904, when a method was developed for the extraction by drilled wells of sulphur of similar origin occurring in the cap rock of some of the salt plugs on the Gulf Coast of Louisiana and Texas.

Over half of the sulphur consumed in the United States goes into sulphuric acid. Sulphur fumes produced by the smelting of sulphide ores are likewise transformed into sulphuric acid, which is very important to industry. It is used for many purposes, including the manufacture of acid fertilizers, chemicals, dyes, and explosives, petroleum refining, sugar processing, in storage batteries, and in galvanizing. Next in importance to sulphuric acid are other compounds used in paper manufacture, refrigerants, fumigants, bleaching agents, and chemicals. Sulphur is necessary also in vulcanizing rubber. Other uses for sulphur are in insecticides, fertilizers, and match heads.

Siliceous deposits. Even silica, the oxide of silicon that in crystalline form is quartz, is slightly soluble in water. Silica is carried to the sea by the rivers draining the continents. It is chemically precipitated on the ocean floor in colloidal (gelatinous) masses. The conditions favoring this precipitation are the same as for calcium carbonate; therefore, such siliceous deposits occur in most cases in limestone. Burial subjects the colloidal masses to pressure, so that the water is squeezed out and the silica becomes hard white *chert* or black *flint,* both submicroscopically crystalline varieties of quartz. These minerals occur in nodules, lenses, and even in beds. Many limestones are cherty; a few formations consist almost entirely of this material. Hot spring waters, beside depositing calcareous tufa, may also precipitate silica. Such deposits are called *siliceous sinter.*

Sedimentary iron ore. The great iron deposits that extend from the Birmingham distirict in Alabama to New York are sedimentary. The ore mineral, hematite, occurs in beds which are inter-stratified with other sedimentary rocks. Iron oxide is present in small amounts in all bodies of water and is precipitated when the water evaporates. Iron can also be removed from solution by iron-secreting bacteria. England and Europe contain deposits of "bog iron ore," consisting mainly of iron carbonate which apparently was precipitated from swamp waters abnormally high in iron.

Diatomaceous earth. Diatoms lived in such abundance during recent geological periods that their tests accumulated in thick deposits on the floors of lakes and seas. Subsequently they became compacted into beds of diatomaceous earth, a white powdery material, light in weight, which is used mainly for heat insulation and as an abrasive.

Phosphate rock. The original source of phosphate is the mineral apatite, which contains calcium, phosphorus, and one or two other elements. Apatite is present in all igneous rocks in minor amounts. Phosphorus, as phosphoric acid, is readily removed from apatite by weathering processes. Phosphoric acid enters the soil where it may replace carbon dioxide in limestone to produce calcium phosphate, or it may be removed by organic life. The organic phosphorus may subsequently be dissolved by ground waters and reprecipitated in calcareous rocks as calcium phosphate in the same manner as phosphoric acid derived directly from the weathering of apatite.

At present the principal source of phosphate in this country is in the states of Florida and Tennessee, where phosphatic rock occurs in sedimentary beds. Great reserves of phosphate in somewhat similar deposits occur in the northwestern part of the United States, especially in Idaho and Montana. The phosphate demand in other parts of the world is met by exportation from the United States, and by exploitation of deposits of phosphate rock in northern Africa.

Coal. Coal may be defined as *vegetal matter with varying amounts of mineral matter which through geological processes has become so changed by loss of volatile constituents that it is compact and dark in color.* Geologists have obtained much factual information through detailed examination of coal beds and associated rock strata from which the steps in the coal-making process have been inferred. Most coal is consolidated and metamorphosed peat. Peat is accumulating at the present time in swamps and lakes scattered over the earth's surface. However, the great coal-making peat swamps of the past were many times larger than those of today. One reason is that the continents at present have much greater relief than they had during most of the past. It is essential to large-scale peat accumulation that a region be near base level, for otherwise streams would bring in so much inorganic sediment that the accumulating organic material would be subordinated, and a carbonaceous shale instead of a coal bed would be the eventual result. Plant fossils found in coal are of the fresh-water swamp type. However, fauna suggestive of brackish (slightly saline) water may also be present. It is probable that most coal originally was peat in coastal swamps, like those between barrier beaches and the mainland in regions of recent coastal elevation. Because many coal beds are overlain by marine strata, it is apparent that oscillations of sea level took place which caused alternation between swampy conditions and complete submergence.

A rather special set of climatic conditions also was necessary in order to create the great peat swamps of the past. The temperature must have been mild, permitting the growth of plants of sub-tropical and tropical habitat. It was also remarkably uniform the year round. The humidity must have been high in order to permit prolific plant growth. The great coal-making periods were marked by a wide simultaneous geographic distribution of favorable climatic environments, for coals belonging to these periods are found on all continents and at widely varying latitudes.

Coal geologists have evolved two theories to account for the accumulation of vegetal matter. One is the *in situ* (in place) theory, the proponents of which believe that the peat of the past which eventually made coal accumulated through the heaping up of the remains of successive generations of plants in successive layers. This process is going on today in large swamps such as the Dismal Swamp of Virginia and North Carolina. The followers of the other concept, known as the *transportation* theory, believe that peat is an accumulation in lakes and lagoons of vegetal matter that has floated in and sunk to the bottom. Wind-blown organic material, such as spores and pollen, are added to this muck. Eventually the lake becomes shallow through the accumulation of organic debris, so that plants of the swamp type take root, grow, and are finally added to the rest of the organic material. Evidence can be found for both theories and it is probable that coal beds have been formed by both methods. Certainly the spores and pollen composing one type of coal (cannel), and also present in lesser amounts in the predominantly woody types of coal, are transported.

The first series of chemical changes necessary to coal formation takes place while the plants are accumulating and fermenting in the swamp. The organic material becomes disintegrated, decomposed, and reduced. To a considerable extent these transformations are brought about through the activity of bacteria and other microorganisms; as a result this step is spoken of as the *biochemical* stage.

The final step in coalification is the *dynamochemical* stage. The disintegrated and "rotted" plant matter becomes buried (following submergence) under scores, hundreds, and even thousands of feet of younger sediments. The weight of the overlying rock compacts the organic material and squeezes out a large share of the water. Burial also raises the temperature, which speeds up the chemical processes so that a part of the volatile constituents escape, and the percentage of fixed (non-volatile) carbon becomes correspondingly greater. If relatively high temperatures are reached, or if the dynamochemical processes continue for a long period of time, coals higher in fixed carbon result. Dynamochemical processes may be accelerated by horizontal pressures and increased temperatures accompanying diastrophism (Chapter 11). Thus the anthracite coal in the Appalachians occurs where the mountain-building forces were much greater than they were in the bituminous coal belt to the westward. The coals occurring between Puget Sound and the Cascade Mountains in the State of Washington consistently increase in rank from west to east toward the zone of greatest diastrophic activity.

Elevation of the coal-containing formations and erosion of the overlying rocks so that the coal beds lie close enough to the surface that they may be exploited are the final processes in the evolution of a commercial deposit of coal (Fig. 111). However, the same processes make coal beds liable to penetration by ground waters, so the

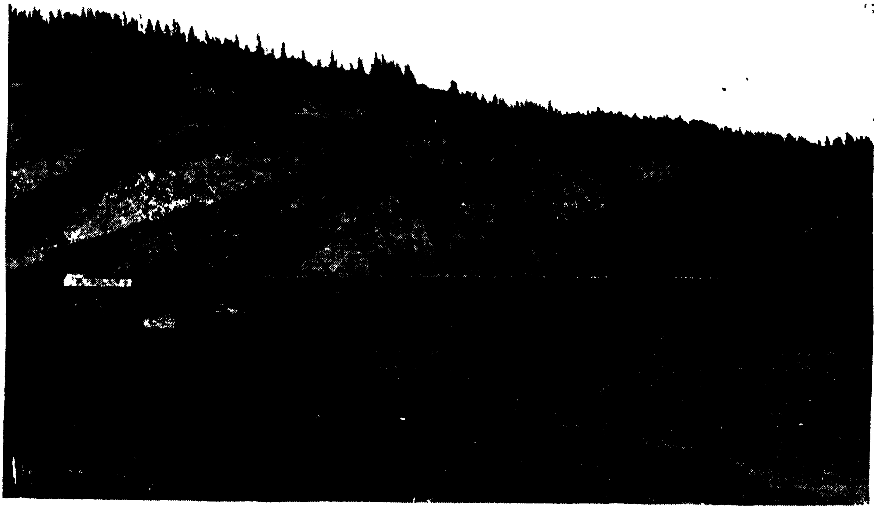

Fig. 111. Four thick inclined beds of coal exposed on wall of cliff in valley of Healy River, Alaska. *By P. S. Smith. Courtesy Geological Survey, U. S. Department of the Interior.*

moisture content of the coal may be increased, and undesirable mineral compounds, such as iron sulphide, may be precipitated within the coal.

Coal is classified into several ranks depending upon both physical properties and chemical composition. *Peat* is plant debris which has not yet reached the true coal stage. It varies from a light brown mass of fibers to a dark brown or black, jelly-like substance. *Lignite, or brown coal,* is the lowest of the true coals. It splits into slabs upon drying. *Sub-bituminous* coal, or *black lignite,* is a slightly higher grade of black coal with a tendency to split irregularly. *Bituminous* coal is deep black and has a cubical or prismatic fracture. *Cannel* is a variety of bituminous coal made up of spores, pollen, and other exceedingly minute plant particles. It has a dull luster and a very homogeneous appearance because of the small size of the component particles. *Semi-bituminous* is high-grade bituminous coal, whereas *semi-anthracite* is low-grade anthracite coal. *Anthracite* is a hard, black, brittle coal. It has a very bright luster and conchoidal fracture (breaks along curved surfaces). *Super-anthracite* coal lies between anthracite and *graphite,* which is pure carbon. Graphite cannot be considered a coal because it will not burn, although some graphite results from extreme metamorphism of coal.

The United States contains enough coal within 3,000 feet of the surface to last for about 1,500 years at the present rate of consumption. The leading coal-producing states are Pennsylvania and West Virginia. The United States ranks first among the nations; this country, Germany, and England together produce nearly three-fourths of the total annual coal output of the world.

Peat and every grade of coal from lignite to anthracite are used for domestic heating and cooking. Various grades of bituminous coal are burned to make steam in ships, locomotives, and stationary boilers. The use of coal to make steam for the generation of electricity is increasing. *Coke* is the hard residue obtained by heating coal in the absence of air. It is a much more concentrated fuel than coal, and is used mainly in metallurgical processes.

PETROLEUM AND NATURAL GAS

Although oil and gas are not ordinarily considered rocks, they occur in sedimentary rocks and have an origin somewhat similar to that of coal. The major difference between coal and oil is in the migratory character of the latter.

Petroleum is essentially a mixture in varying proportions of different hydrocarbons (substances composed of hydrogen and carbon). Beside liquid hydrocarbons there are also gaseous hydrocarbons, such as natural gas, and solid hydrocarbons, including paraffin and asphalt. Both gaseous and solid hydrocarbons may be dissolved in crude oil, especially where it is deeply buried in the crust and consequently under great pressure.

Crude oils vary in color from light amber to black, depending upon their composition. A most important property of crude oil is its density, or "gravity." Light oils have a relatively high gasoline yield and are in most instances capable of producing a higher grade of lubricating oil than the heavier crude oils. The heaviest oils have about the density of water, but the average petroleum is considerably lighter than water.

Many problems concerning the occurrence of oil have not been solved to the satisfaction of everyone. Several theories based on an inorganic source of oil have been advanced, mainly by chemists. These theories, although readily demonstrable in the chemical laboratory, are very strongly opposed by geologists who have at their command a vast amount of information in regard to the manner in which oil occurs in the rocks of the earth's crust. Geologists believe that oil was originally organic material, because it is almost invariably associated with sediments and is absent in igneous rocks where inorganic oil would be expected to occur. Bituminous rocks are found in the vicinity of most oil fields, and a petroleum-like fluid can be distilled from such rocks by a simple laboratory process. Furthermore, oil from organic material, both plant and animal, can be obtained just as readily in the chemists' laboratory as oil from inorganic material.

For many years a controversy has waged among petroleum geologists as to whether oil comes from animals, plants, or perhaps from both types of life. The soft body parts of marine animals, such as fish, corals, clams, snails, and foraminifera could, if accumulation took place in sufficient amount, yield oil. It is true that skeletons or shells of these animals are very abundant in many marine formations now lying at or near the earth's surface. However, there is some question as to whether or not the bodies of the skeleton- or shell-building animals ever accumulated in volume approaching that of the harder parts, because sea-floor scavengers would dine on these carcasses.

It is not possible to consider land animals as having been a source of oil because (1) they were not abundant until relatively late in geologic time, (2) decay is too rapid on the surface of the land for the accumulation of carcasses, and (3) oil is usually in and associated with marine strata.

The proponents of the plant theory for the origin of oil believe that the lower plants and finely divided higher plants, especially spores and pollen, furnished the source material for petroleum. Both marine and continental plants are possible sources, for the latter may be carried to the sea and deposited under a marine environment.

It is possible that petroleum is derived both from marine animals, especially the microscopic one-celled types, and from the lower plants, many of which are likewise microscopic and one-celled, with perhaps some finely divided, higher plant material.

Rocks containing organic materials suspected of yielding oil are known as *source rocks.* Recent and very extensive investigations into the probable character and environment of source rocks have resulted in the conclusion that the best source rocks are marine sediments which were deposited fairly close to shore and which are either shaly (claycy) or calcareous (limestone) beds. Therefore, conditions are unfavorable for oil where the rocks were deposited in fresh water or, if marine in character, where the sediments were deposited in deep water and far from shore. The real source beds of oil are probably less bituminous than oil shales, which are fresh water deposits.

Next is the conversion of the organic material in the source rocks into petroleum. The first step in this process is biochemical, during which bacteria decompose the organic material and remove the oxygen that is present in all plants and animals but is not an essential constituent of petroleum. The biochemical action takes place while the organic material is accumulating on the sea floor. Subsequently the somewhat altered organic debris is covered by a layer of clay or mud.

Burial is followed eventually by a transformation of the solid organic matter into liquid petroleum. Questions as to the details of this conversion are largely unanswered. From laboratory experimentation it is known that either unusually high temperatures or pressures sufficiently great to cause molecular displacement will produce transformation of solid carbonaceous matter into petroleum, but most oil regions show no evidence of the existence of abnormal temperatures, or high rock pressures, since the oil-bearing sediments were deposited. Perhaps the answer to the enigma is that the transformation can and does take place at near-normal temperatures and pressures, but the process is so slow that time must be measured by geological standards before appreciable results are obtained. The laboratory technician can simulate most of the conditions which nature may impose upon materials in the earth's crust, but he cannot simulate geologic time. A million years is not a very significant length of time to the geologist, but results could presumably be obtained in that span of time that would not be noticeable in a few years of laboratory operation.

The next step in the accumulation of oil is its *migration,* for commercial quantities of petroleum are not obtained from source rocks because the permeability of such rocks is so slight that oil will not move through them into a well. Instead it migrates very slowly and through a long period of time from the source rock into a more porous formation, known as the *reservoir rock.* A reservoir rock must have an abundance of open spaces. If oil or gas are not present, these openings are, in most cases, filled with water. The *voids* or open spaces in rocks such as sandstone are merely the pores between grains of sand. The better the rock is cemented, the less space is available for liquids and gases. Other types of voids are cracks and fissures cutting through the rock, solution cavities (especially abundant in some limestones), and cavities formed during the weathering of other types of rock.

The two essentials of a reservoir rock are that it must have enough voids to permit the storage of a large volume of oil and that it must be sufficiently thick so that a well will yield enough oil to more than pay for its drilling. Furthermore, the voids must be coarse enough to permit fairly rapid movement of the oil through the rock into the well. A shale may be as porous, and therefore may contain as much oil, as a sandstone, but the oil will move through the shale's very fine pores at such a slow speed that commercial production will not be possible.

The most common reservoir rocks are sandstones, with limestones and dolomites second. Conglomerates yield oil in a few fields. In rare instances, oil is obtained from a zone of weathering cavities at the top of ordinarily impervious igneous or metamorphic rocks.

Reservoir rocks are not everywhere filled with oil; in fact, they usually contain many times more water than oil. But here and there the oil may be "trapped" in a relatively small part of a reservoir rock, and the drilling of a well at such a place may result in the discovery of a new oil (or gas) field. Trapping of oil and gas is due mainly to movements of the earth's crust; therefore, consideration of this phase will be postponed until Chapter 11, in which diastrophism is discussed.

The United States produces more crude oil than the total output of all the other countries. The proportion of world oil annually produced by the United States ranges between 60 and 70 per cent. The greater part of the total domestic production has come from three states: Texas, California, and Oklahoma.

CHAPTER 10

Vulcanism and Igneous Rocks

VULCAN, IN ROMAN MYTHOLOGY, WAS THE god of fire. Vulcanism is the name that has been applied by geologists to all manifestations of heat within the earth. It includes not only volcanoes, which are confined to the surface of the earth, and the hot liquid rock which solidifies below the earth's surface, but also the many by-products of this activity, including some of our greatest deposits of valuable minerals.

Magmas. Igneous rocks are formed through the consolidation (freezing) of a *magma.* A magma is a very hot *solution* of rock materials. When its temperature is lowered, the various dissolved compounds separate out as solids, and these solids are minerals. In rare instances the chilling is so sudden that no separation takes place, and the magma freezes into a natural *rock glass* such as the *obsidian* of Yellowstone Park.

Magmas move from the interior of the earth toward the surface. During the upward movement the magma is cooled by contact with rocks of lower temperature, and, eventually, solidification takes place. Sometimes the magma reaches the surface before it freezes, in which case we call it a *lava.* Inasmuch as the temperatures at the earth's surface are far below the temperatures at which a magma can remain in liquid form, most lavas solidify before they travel any great distance.

Magmas vary considerably in composition. The most common magmas are chemically similar to the crust of the earth, consisting of about three-fourths oxygen and silicon and nearly one-fourth aluminum, iron, calcium. sodium, potassium, and magnesium. From a chemical standpoint a magma is best described as *a complex solution of silicates.* In addition to silicates, magmas also contain a number of elements and compounds which are called *fugitive* because they tend to escape while the magma is undergoing solidification. The most abundant of these fugitive substances is water. Other fugitives are chlorine, fluorine, carbon dioxide, sulphur, and a host of rarer elements and compounds. Many of these substances are gaseous (at least at magma temperatures), but these gases are dissolved within the magma by the pressure that exists beneath the surface. However, when a magma approaches the surface, the pressure diminishes and the gases tend to escape. A familiar analogy is soda water, which is water with carbon dioxide, a gas, held in solution by pressure. When the bottle cap is removed the pressure is released and the soda water bubbles, or effervesces, in the escape of the carbon dioxide. Lava at the surface bubbles (giving the impression of boiling) in the same manner. Scientists have trapped and analyzed the gases given off by volcanoes.

Until a few years ago it was believed that the earth consisted of a thin rock shell overlying a liquid interior. According to this theory, a volcano occurred where a crack in the earth tapped the subcrustal liquid. Now we know, however, through evidence that will be discussed in Chapter 12, that the interior of the earth is solid down to a depth of 1800 to 1900 miles. We also know that this solid rock is hot; in fact the earth temperatures a relatively short distance below the surface are so high that they would melt the rock if it were under atmospheric pressure only. But *melting points of rocks increase with increase in pressure,* and the pressure exerted by the weight of overlying rock is more than sufficient to raise the melting point above the rock temperature so that fusion is impossible. However, if the pressure is temporarily released at any point, liquefaction of the rock might take place, producing a magma.

How igneous rocks are formed. The probable sequence of events leading from deeply buried, highly heated, solid rocks to igneous rocks at or near the surface is as follows: First, movements of the earth's crust, such as take place on a large scale when mountain-building forces are at work, cause a release of pressure on a body of deep-seated material. Liquefaction occurs and the magma moves upward. One reason for this upward movement is the squeezing effect of the neighboring rock where the pressure has not been released. A second possible reason is the tendency of the fugitive constituents of the magma to escape, carrying along a part of the magma as they do so. This process is analagous to the foaming of an agitated bottle of soda water or beer. The final step is the solidification of the magma, forming igneous rock. As the magma moves upward, successively cooler temperatures are encountered which may cause consolidation before the surface is reached. In this case the magma is called an *intrusion,* and the resulting igneous rock is called *intrusive rock.* A magma which reaches the surface and flows out as a lava is called an *extrusion,* and the resulting igneous rock is called *extrusive rock.*

Igneous extrusions will be discussed first in the following paragraphs because, owing to their accessibility, we know much more about them. This knowledge has been used in formulating our ideas about igneous intrusions.

IGNEOUS EXTRUSIONS

There are two types of igneous extrusions: (1) *fissure eruptions,* where the lava pours out of a crack in the earth's crust, and (2) *central eruptions,* where a pipe-like conduit brings the lava to the surface. The latter type of extrusions produces a *volcano.*

Fissure eruptions. If lava moving up a crack or fissure reaches the surface, it will pour forth at many points and inundate a large area. Since the dawn of human history many volcanoes have been active, but there have been relatively few fissure eruptions. However, one series of fissure eruptions may produce as much lava as many volcanoes. We know of great plateaus that have been built up by fissure eruptions in the fairly recent geologic past. Some of these contain hundreds of cubic miles of lava.

A description of a witnessed fissure eruption will give some idea as to what takes place. In Iceland in 1783 lava welled out of a fissure 20 miles in length for several months. Instead of flowing out like an inverted fiery waterfall, most of the lava poured out from individual points along the fissure, and over a hundred low craters were formed. The lava flowed for a distance of 27 miles down a canyon-like river valley, completely filling it and overflowing onto adjacent fields. Tributary streams were dammed by the lava so that the water backed up and flooded many villages. A second lava torrent flowed 28 miles in a different direction. Lyell, famous British geologist (1797-1875), has the following to say about the destructive effect of this fissure eruption:

> Although the population of Iceland was very much scattered, and did not exceed fifty thousand, no less than twenty villages were destroyed, besides those inundated by water; and more than nine

> thousand human beings perished, together with an immense number of cattle, partly by the depredations of the lava, partly by the noxious vapours which impregnated the air, and, in part, by the famine caused by showers of ashes throughout the island, and the desertion of the coasts by the fish.[1]

The Columbia River plateau of eastern Washington, eastern Oregon, northeastern California, and southern Idaho is a mass of lava covering thousands of square miles and in places over a mile in thickness. The eruptions producing this plateau took place in fairly recent geologic time, but before the advent of man. Where the Columbia and Snake rivers have carved their valleys into the plateau, many vertical and steeply dipping dikes (lava-filled cracks) are exposed. These may have been the "feeders" which supplied the lava to the surface. The Columbia River plateau is built up of many separate flows. A sufficiently long period of time elapsed between some of the eruptions to permit shallow lakes to form on the lava surface in which sediment was deposited and various types of plants grew. Recent erosion has exposed some of these lake beds with their remains of plant life, including petrified wood.

The Deccan Plateau of India was likewise formed through a great series of fissure eruptions.

Volcanoes. Earthquakes and volcanoes are two geological processes that are catastrophic in their behavior. A river takes many centuries to carve out its valley, but an active volcano in a few minutes or less can blow its cone, which may be a large mountain, to pieces.

Volcanoes are to be found in many parts of the world, but the greatest number border the Pacific Ocean. Starting at the southern tip of South America, a line of volcanoes extends north along the western edge of South and North America. The volcano zone bends southwestward in Alaska, following the Alaskan Peninsula and its continuation, the Aleutian Islands, to Asia. The Aleutian Islands are volcanoes whose summits rise above sea level. The Asiatic volcanoes extend from Kamchatka, bordering the North Pacific, through the many islands in the Japanese chain, to the Dutch East Indies.

Many of the volcanoes which surround the Pacific are dead, some are merely dormant, and a few are active. One can never be positive whether a volcano is dormant or dead. If the volcano has been inac tive for such a time that erosion has in part destroyed the cone, it may be assumed to be dead. However, even then one cannot be positive, as some of our most destructive eruptions have been caused by the awakening of supposedly dead volcanoes. Among the most famous volcanoes today are Etna, on the Island of Sicily, Mont Pelee, on the Island of Martinique in the West Indies, Lassen in California, the new Paricutín in Mexico (Fig. 112) and Kilaeua in Hawaii. The Hawaiian Islands are a row of volcanic cones which rise sufficiently high above the sea floor to make islands.

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[1] Lyell, Sir Charles, *Principles of Geology*, 11th ed., Vol. 2, 1889, p. 51.

Some of our most beautiful mountains are extinct volcanoes. Many stand apart from the main mountain ranges and rise to majestic heights in solitary grandeur. Examples of this are Shasta in California, Hood in Oregon, and Rainier in Washington. Some volcanoes, such as Mount Fujiyama in Japan, are famous for their nearly perfect conical symmetry. The top of a volcanic cone has, until destroyed by erosion, a *crater,* a circular depression with its lowest point at the "throat" of the volcano.

Explosive volcanoes. Volcanoes can be classified in

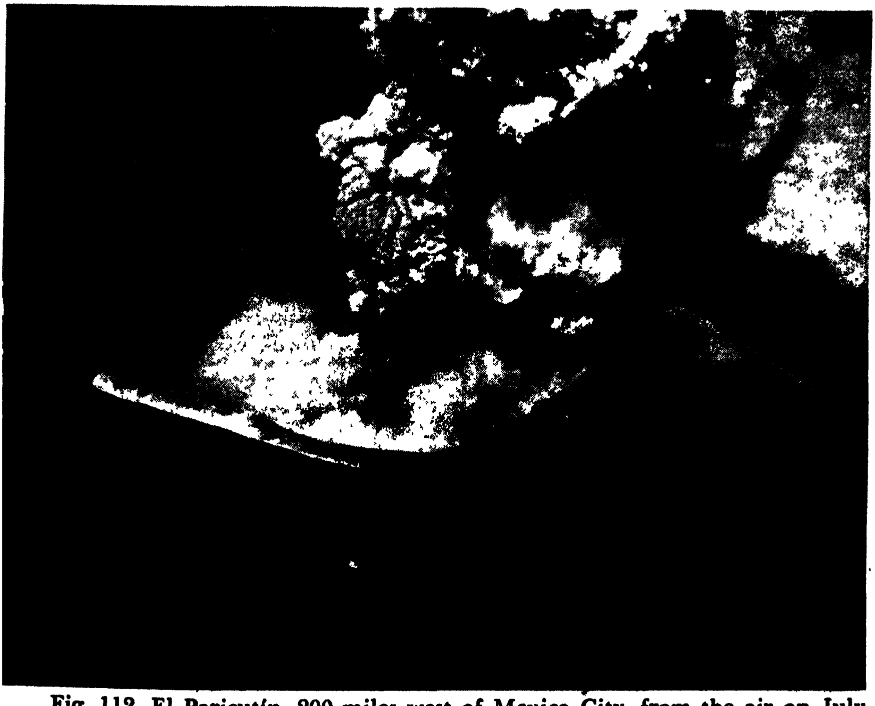

Fig. 112. El Paricutín, 200 miles west of Mexico City, from the air on July 31, 1945. ***By W. F. Foshag.***

three types: explosive volcanoes, quiet volcanoes, and volcanoes which alternate in character of eruption between explosive and quiet. Three kinds of material are ejected by an explosive volcano. These are gas, volcanic ash, and fragmental rock (Fig. 113). The gas consists of water vapor, compounds of sulphur, and various other elements. A few volcanoes have erupted a gas which caused the death of people breathing it, but as a general rule volcanic gas, although not exactly pleasant to smell and decidedly injurious to vegetation, does not have a fatal effect upon human beings. *Volcanic*

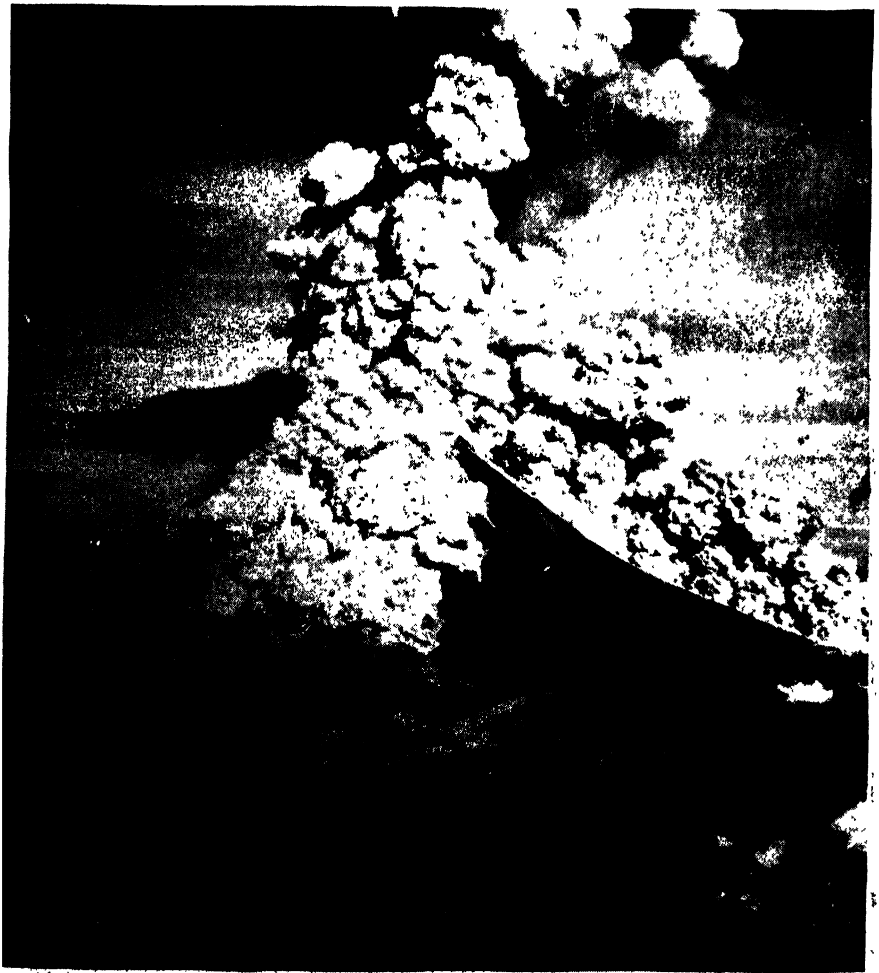

Fig. 113. Eruption of Mt. Mayon, northern Luzon, Philippine Islands. An explosive volcano, with cone built of fragmental material. *Courtesy Keystone View Company.*

ash consists either of very fine particles of natural rock glass formed by the sudden chilling of fine drops of lava thrown into the air during the eruption, or, in the case of very violent explosions, of small particles of the volcanic cone itself which was torn asunder by the mighty force of the explosion. In either case the ash is so fine that some of it may be carried many miles by the wind, as described in Chapter 3, before falling to the earth's surface. But the greater part of the ash falls in the immediate vicinity of the volcano, sometimes to a sufficient extent to bury villages and suffocate the inhabitants who fail to make their escape. The fragmental rocks vary greatly in size and shape. The smallest fragments are called *"cinders."* Some of the larger pieces are spherical or pear-shaped and are known as *"bombs"*; others are irregular in shape. Most of the fragmental material is black, but *pumice* is light in color. It is a rock glass, like volcanic ash, and is so full of holes formed by escaping gas that some specimens will float on water. The fragmental rocks are too heavy to be carried by the wind, so they travel no farther than the force of the explosion will take them. Most of this material falls on the flanks of the volcano, and each explosion builds it up to a greater size. Volcanic cones built of ash and fragmental rock are known as *cinder cones.*

Cinder cones are readily distinguished even at a distance from lava cones. The fragmental material that is ejected piles up into a cone with fairly steep flanks, whereas lava, being a liquid, flows outward from the crater for some distance before solidifying, and forms a cone which has a diameter many times its height. All of our volcanic peaks of great height and spectacular appearance, such as Fujiyama, Rainier, and Shasta, are cinder cones or combinations of cinder and lava cones.

Probably the best way to learn about volcanic phenomena other than actually seeing an eruption is to read the accounts of eyewitnesses. The first well-described volcanic eruption was that of Vesuvius in 79 A. D. Pliny the Younger witnessed this eruption and the letters which he wrote to a friend describing the scenes which took place and the tragic death of his uncle, Pliny the Elder, have been preserved.

On the 24th of August, the younger Pliny, with his mother and the elder Pliny, observed a cloud of unusual appearance and size rising from one of the hills which they later determined to be Vesuvius. In describing this cloud Pliny says, "It imitated the lofty trunk and the spreading branches of a pine, for either the smoke had been swept rapidly upward by a recent breeze and was then left hanging unsupported or else it spread out gradually by its own weight and grew thinner. It changed color, sometimes looking white and sometimes, when it carried up earth or ashes, dirty and streaked." Soon after the cloud was first observed, ashes began to fall on the war vessels commanded by Pliny the Elder. Also there began to break out from Vesuvius high- and wide-shooting flames, the brilliancy of which was heightened by the darkness of approaching night. Pliny the Elder went ashore and took refuge in a house which tottered with frequent and heavy shocks of earthquakes. There he and his friends spent the night, but because of the great quantities of ash in the air, the next morning found the vicinity still plunged in darkness. In spite of the dangers of falling pumice stones outdoors, Pliny and his companions decided to leave the house and see if the sea would allow them to embark, but the constant earthquakes made the waves run dangerously high. Pliny lay down on a rug, and many hours later, when light finally penetrated the atmosphere, his body was discovered. He had been suffocated by the vapors. Meanwhile the younger Pliny and his mother had taken refuge across the bay where they joined the terror-stricken populace as it retreated before the advancing clouds of ash-laden atmosphere. The nearby town of Pompeii was completely buried by the fall of ash, and the citizens of those towns who failed to escape were suffocated like the older Pliny and subsequently entombed by the long-continued fall of ash.

Great as this eruption was, it was surpassed but a few decades ago by the outbreak of Krakatoa. Krakatoa is a small island lying between the greater islands of Java and Sumatra in the South Pacific. When the volcano composing this island erupted in 1883, it made what is undoubtedly the world's greatest explosion in historic time. In two days about one-half of the island either blew away or collapsed into an underlying void, so that now the sea is 1,000 feet deep where the central part of a mountain formerly stood. Ash was thrown to a height of 17 miles and was carried completely around the world, causing for many months brilliant sunrises and sunsets on all continents. Ships 1,600 miles distant were covered with dust three days after the eruption. The noise of the explosion was heard 2,000 miles away. In other words, if a similar eruption were to take place today at the Panama Canal, the noise could be heard in New York City.

It would take the sound over two hours and a half to cover that distance. The island of Krakatoa was uninhabited at the time of the eruption, so no lives were lost directly, but the shock produced waves from fifty to eighty feet high which swept the adjacent shores, wiping out over a thousand villages and drowning about 35,000 people. These waves were so strong that a large vessel was carried a mile and a half inland and left stranded there at an elevation of thirty feet above sea level.

A most terrible disaster took place in 1902 on the French island of Martinique in the West Indies. The volcano of Mont Pelée, which had been mildly active for some days, suddenly belched forth a great cloud of gaseous vapor which was so hot as to be incandescent. The gas was heavier than the air, so it ran as a great devastating torrent down one flank of the volcano through the city of St. Pierre, at that time the leading seaport on the island, and out to sea. The city was at once destroyed. Those inhabitants that were not burned to death were suffocated by the vapors. Even the ships anchored in the harbor were not safe. All but one vessel was destroyed, and everyone on board perished. The loss of life which took place in but a few seconds time has been estimated at 40,000.

A more violent but less disastrous explosion was the eruption of Katmai, a volcano on the Alaskan peninsula, in 1912. This eruption took place in a region that was very thinly populated. The nearest settlement of any size was on the island of Kodiak, about 100 miles distant. The people living on this island were in total darkness for sixty hours, and the fall of ash was great enough to collapse some of the roofs. The sound of this explosion carried about 750 miles. Large amounts of sulphurous vapors were also expelled into the air during the eruption, and subsequent rains falling on the North Pacific coast became so acidic that clothes hanging outdoors were destroyed.

"Quiet" volcanoes. Much less spectacular but a little more pleasant to have as a neighbor is the quiet type of volcano. Such a volcano produces lava and gas, but little or no ash and fragmental material. As stated before, the cone produced by a quiet volcano has very gentle slopes. It is built up through the solidification of successive outpourings of lava. Crater rims are never exactly level, unlike the top of a bowl, so the lava does not pour out as water boils out of a pan on the stove. Instead the lava escapes through the lowest point in the crater rim and flows down one side of the volcano

in a tongue-shaped torrent. When the flow solidifies it partially fills the notch in the crater rim, so that the next flow may have to find another avenue of escape. In this way successive lava flows shift around the volcano and tend to build it up symmetrically. As a matter of fact, in a great many volcanoes only a relatively small amount of the lava flows out from the crater; the remainder breaks through the cone at lower elevations and flows down the flanks as though from a spring, sometimes flowing some distance beyond the base of the cone (Fig. 114). The lava as it emerges is filled with dissolved gas, which, through the release of pressure, escapes with considerable violence, and whips the surface of the lava into a froth. In many instances solidification is so rapid that the frothy surface of the lava congeals in that condition. Such lava is called *vesicular* or *scoriaceous.* Movement of the still-liquid underlying lava may cause the "jamming" of the solidified surface of the flow (Fig. 115).

Perhaps our best known examples of the quiet type of volcano are Mauna Loa and Kilauea in the Hawaiian Islands. The United States Government has maintained a volcano observatory on the

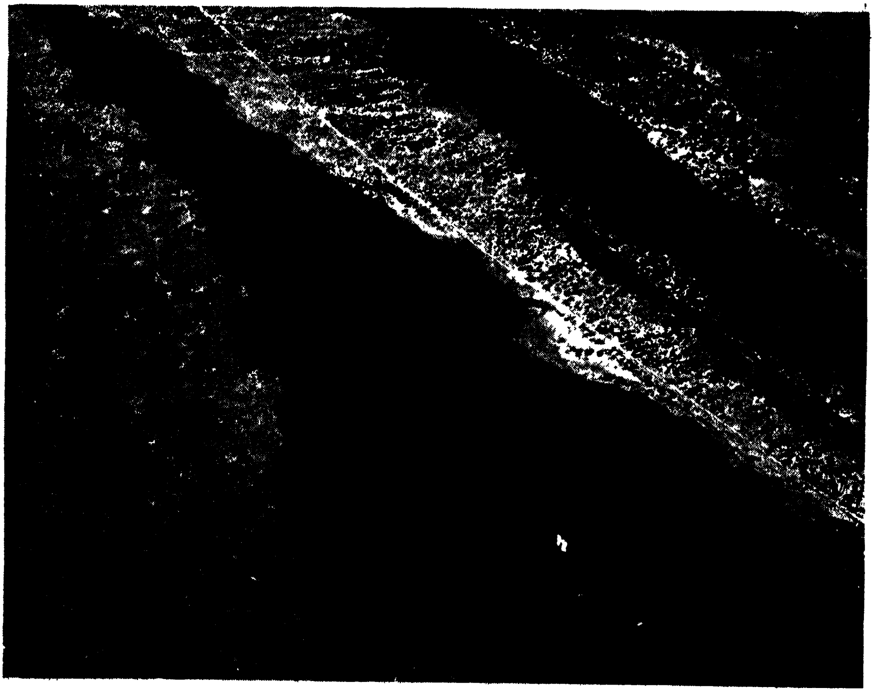

Fig. 114. Tongue of congealed lava extending down valley. Near Grants, New Mexico. *By permission of Fairchild Aerial Surveys, Inc., L. A.*

rim of Kilauea for a number of years. These volcanoes end a period of dormancy with a number of mild explosions which take place in the crater and which cause local earthquakes. The explosions are accompanied by occasional overflow of lava. Other bodies of lava break through the cone and flow down the gentle flanks toward the sea. Sometimes the lava reaches the island coast before solidifying and drops over the wave-cut cliffs into the ocean. One very interesting phenomenon of these flows is the formation of tunnels within the lava. A tongue of lava cools and solidifies first on its bottom and top surfaces, where it is in contact with cooler rock and with the air. Where the slope is sufficient, the still-liquid lava in the core of the flow may drain on out, leaving a tunnel.

> [2] Volcanoes do not pour their rivers of lava down the luckless countryside in a clear hell-broth that runs like water over Niagara to waste forests and plantations with flame. "No thin broth, but a very thick porridge," was the simile used by Dr. T. A. Jaggar, volcanologist who lives in a house on the edge of Kilauea's crater. Rivers of lava do not run; they creep. A mile a day was the speed of the lava flow that threatened the town of Hilo some time ago and had to be stopped by airplane bombs.
>
> The forward creep of one of these streams of thick lava is an impressive and very strange thing to watch. As it [the lava] is extruded from the volcano—usually from a crack on its side rather than from the crater—it oozes forth in one big stream. This breaks up into a large number of smaller streams that flow in close ranks side by side, like a hank of rope. This ropy type of lava is called by a name that originated in Hawaii, pahoehoe [Fig. 116]. As each streamlet of the pahoehoe pushes itself forward, it roofs itself over with a thick, solid crust, so that the entire stream comes to flow in a tunnel of its own making. Even the forward end of the lava is covered with a thin crust or membrane, which it constantly breaks through and as constantly re-forms. The moving tip of a pahoehoe streamlet Dr. Jaggar likened to an elephant's toe.
>
> Dr. Jaggar stated that the stopping of the recent flow that menaced Hilo was not a military man's idea, nor yet his own inspiration. At first the proposal was to pack a lot of dynamite to the critical point on muleback, but a planter pointed out that bombing planes could not only find the lava tunnels much more easily in the dense forest but could attack them more effectively when found. Neither was the bombing attack conducted against the moving front of the lava columns. That would not have stopped them. In true modern airwarfare style, the planes struck at the base of operations—the heads of the lava streams just as they emerged from the slope of Mauna

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[2] Thone, Frank, "The Flow of Lava," *Science* (Supplement), May 6, 1938, p. 12.

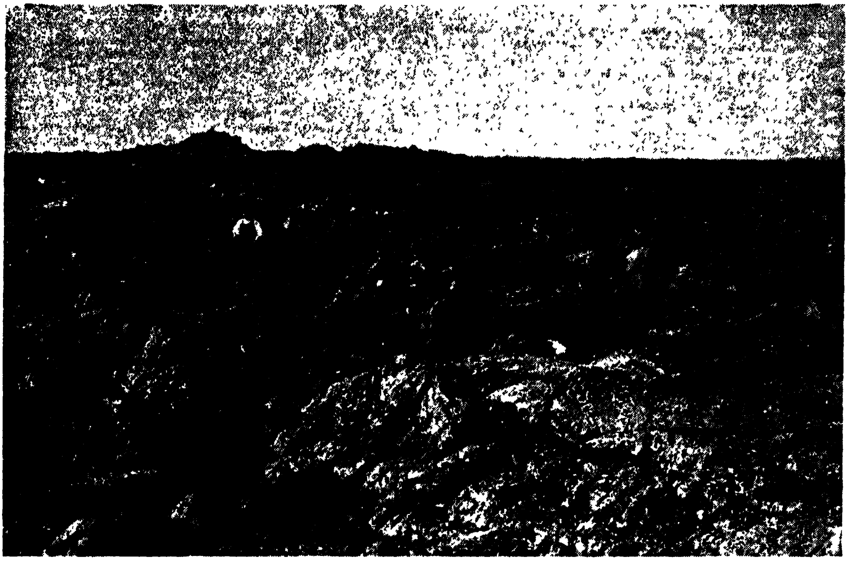

Fig. 115. Lava flow surface near Carrizozo, New Mexico. *By N. H. Darton. Courtesy Geological Survey, U. S. Department of the Interior.*

Fig. 116. Ropy or *pahoehoe* lava in congealed lava lake of Halamaumau, Hawaii. Hammer in center gives scale. *Photo by H. T. Stearns, Geological Survey, U. S. Department of the Interior.*

Loa. With 600-pound bombs of TNT they blasted in the roofs of the tunnels. This permitted the escape of the gases that were the principal source of heat for the lava. With their power supply thus cut off the streams were stopped at their source.

Alternating type of volcano. The alternating type of volcano produces gas and both lava and fragmental material (Fig. 117). A period of quiescence is followed by a violent explosion, which produces the same type of material that is characteristic of cinder cones. As the explosive violence dies down, more and more lava is ejected. Eventually the lava flows cease and another period of quiescence follows. This cycle has been repeated a great many times in some volcanoes.

Mount Mazama in Oregon is a good example of the alternating type of volcano, although toward the end of its eruptive history it passed through some unusual chapters. This mountain was originally built up by a long series of alternating explosive and lava flow phases. According to one theory, the great amount of material, both fragmental and liquid, that was ejected from the volcano left an

Fig. 117. Volcano erupting lava through dike to flank and belching fine ejectmenta in great "smoke" cloud from throat of crater. Ordinarily the explosive phase alternates with the lava eruption phase instead of occurring concurrently. *By John Jesse Hayes.*

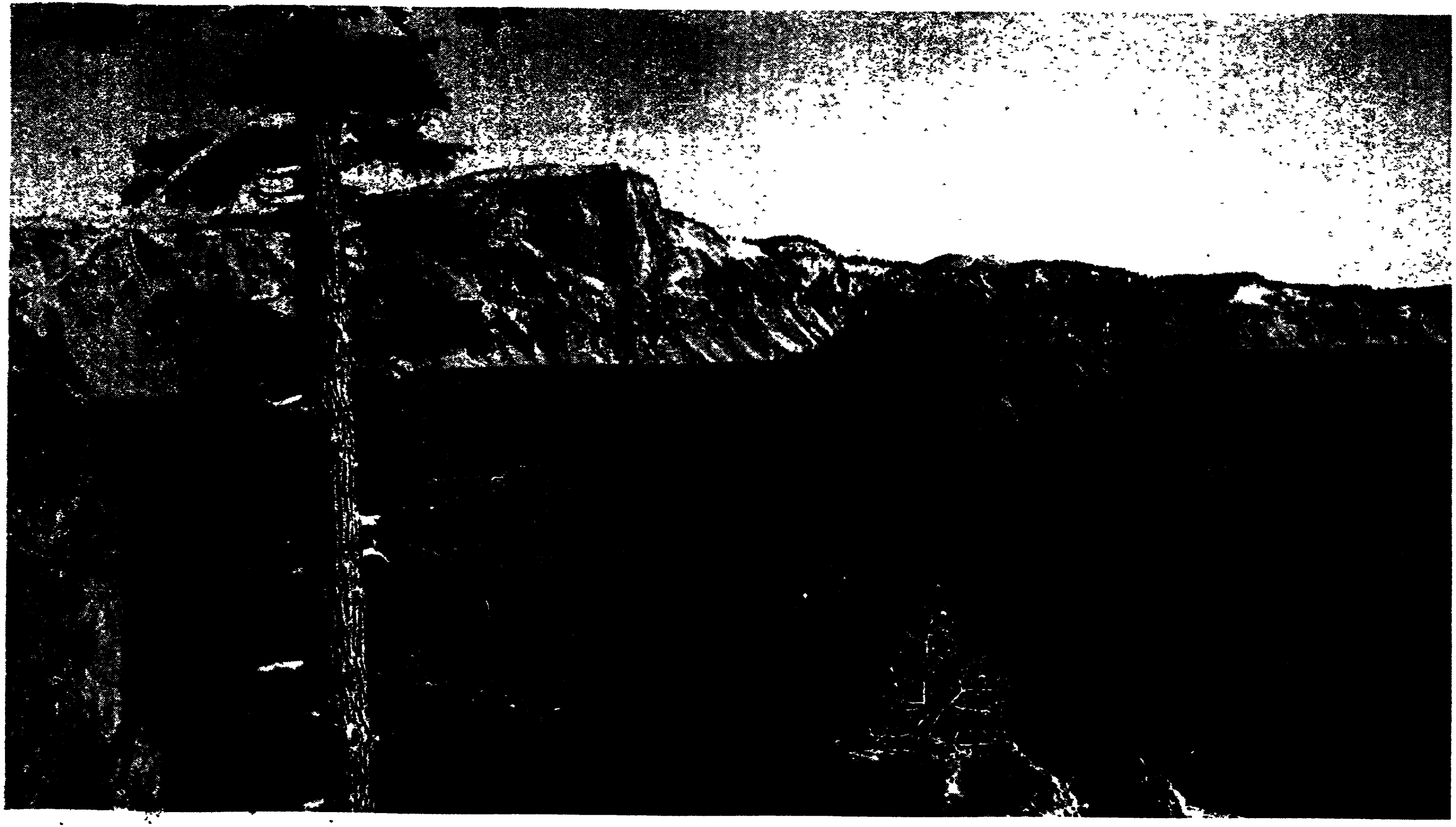

Fig. 118. Crater Lake, Oregon, with Wizard Island, a cinder cone built upon the crater floor, rising above water level. Crater Lake National Park, Oregon. *Photo by George A. Grant. Courtesy National Park Service.*

underlying void which was not refilled from deeper magma reservoirs, so that the entire summit of Mount Mazama collapsed and a gigantic crater was created. A second theory explains the enormous crater as due to a great explosion that blew off the top of Mount Mazama. The collapse or explosion was followed by a relatively feeble renewal of volcanic activity and several small cinder cones were formed on the floor of the large crater. Subsequently this depression has become partly filled with water, making the very beautiful Crater Lake, one of the most interesting, from a geological standpoint, of the national parks (Fig. 118). One of the cinder cones built upon the floor of Crater Lake rises above the water level (Wizard Island). Alternating beds of lava and fragmental material are beautifully exposed about the walls of the crater between the water's edge and the rim.

Eruptive sequence. The following paragraphs give in chronological order the typical volcanic stages:

(1) Lava breaks through the earth's crust to the surface. Volcanoes occur along belts of crustal weakness, such as along the boundary between the relatively high continental masses and the deep ocean basins. Apparently there are also belts of crustal instability beneath the ocean floor, as evidenced by the Hawaiian and other groups of volcanic islands. The lava may reach the surface either through fissures (fissure flows) or through circular vents (volcanoes). As far as volume of lava is concerned the fissure eruptions are much the more important. However, volcanoes are more prominent topographic features, and have been more active in historic time than the fissure eruptions.

(2) The cone is built. A central eruption produces a number of products, including gas, volcanic ash, fragmental material, and lava. The cone is built from either ash and fragmental material, or lava, or both.

(3) There follows a period of dormancy. The lava in the conduit congeals and acts as a cork, effectively preventing further volcanic activity until sufficient pressure is built up beneath the "cork" to blow it out.

(4) Activity is renewed. Usually the first sign of the end of a period of quiescence is the occurrence of a number of local earthquakes. The cork may be melted away, in which case the renewed activity will be mild in nature. Gas will be blown into the air, and lava may

either flow out over the crater rim or through the side of the volcano and down its slope.

In some instances the renewal of activity is marked by a violent explosion. The entire top of the volcano may be blown away, as was the case at Krakatoa and Katmai. Both coarse fragmental material and volcanic ash are blown into the air in great abundance. There may or may not be lava flows accompanying this type of eruption.

(5) New cones may be formed. In certain instances renewal of activity has been accompanied by the building of a new cone or cones on the remnants of the old. Vesuvius is a relatively new volcano built upon the remnants of a very much older one. The volcanoes on the floor of Crater Lake belong in this stage of the sequence.

(6) The volcano expires. This stage may be marked by post-igneous activity. *Fumaroles* (gas vents), hot springs, and geysers may exist for a relatively short period of time. The fumaroles form minerals by gaseous sublimation on the crater walls; the hot springs and geysers deposit about the vent mineral matter which was in solution.

(7) Erosion begins. The cones of volcanoes are subject to the same attack by the atmosphere and running water as are other rocks exposed at the earth's surface (Fig. 119). In time these agents of erosion will completely destroy a volcano, leaving only a neck of igneous rock to mark the site.

Volcanic islands. Volcanism beneath the sea has produced cones which in many places rise above the surface of the water. Such volcanic islands occur mainly, but not exclusively, in the Pacific. The Hawaiian Islands are a group of volcanoes which start upward from the ocean floor 15,000 to 18,000 feet below the water's surface. The highest of these volcanoes, Mauna Kea, is one of the great mountains of the world, with a total height of approximately 32,000 feet, of which nearly 14,000 feet is above water.

Mineral deposits. Minerals occurring in volcanic fumarolic sublimates are of more scientific interest than practical importance. There is no opportunity for mineral deposition during the explosive stage of a volcano, but as activity decreases in violence the escaping fumes may come into contact with the walls of the crater and there deposit various compounds. Metallic minerals do not occur in commercial quantities in such environments. However, some of the volcanoes of Mexico and South America (especially Chile) have yielded commercial supplies of sulphur. Such non-metallic compounds as nitrates, borates, and various salts may occur in this environment.

Volcanoes and man. Although previous pages of this chapter have contained descriptions of some of the devastating effects of volcanic eruptions, volcanism actually benefits mankind. Volcanic soils are noted for their fertility; the lush vegetation of such volcanic regions as the Hawaiian Islands, western Guatemala, and El Salvador testify to this fact. Furthermore, soils in areas of intermittent volcanism are subject to periodic rejuvenation. Crops being grown on the flanks of a dormant volcano may be destroyed by a new eruption, but the finer ejectmenta blown over the surrounding countryside enrich the soil. The mere height of the volcanic cones, especially in the tropics, benefits the people, for the higher altitudes supply different climatic zones in which a wide diversity of agricultural products can be raised. The superior character of volcanic regions, from a land-use standpoint, is shown by by the island of Java with its 32 active volcanoes. The population

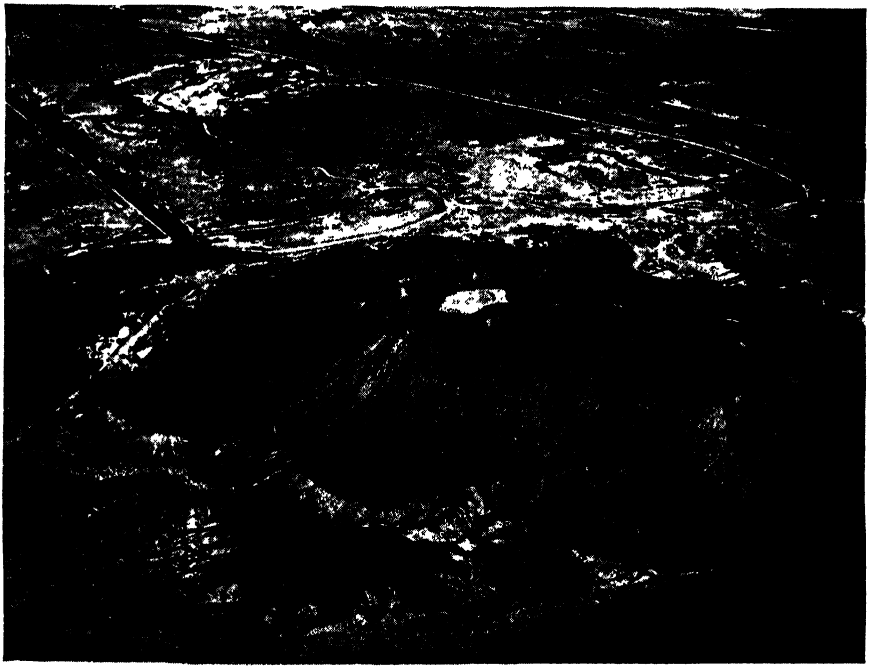

Fig. 119. Cinder cone undergoing attack by agents of erosion. Intermittent stream at lower left has cut through cinder flank, almost completely severing part of cone from remainder. Black Butte, Lower California, 25 miles south of Mexicali. ***By permission Spence Air Photos.***

density of Java is over 850 people per square mile, the highest in the world, and it is based upon an agricultural economy.[3]

At least one instance of successful prevention of hitherto destructive volcanic activity (in addition to the bombing method previously described) is on record:

> The type of mud flow to which attention will now be directed is characteristic of the volcanic activity at the Kloet in Java. Considerable fumarolic activity is present in this volcano, as shown by the roiling of the water in its crater lake. In 1919 an explosion of frightful intensity carried over the rim of the crater a large portion of the water which flowed down the channels on the outer slope. The resulting mud flow rapidly engulfed a large area and killed over 5000 people. The Dutch authorities have now pierced the volcanic edifice with a tunnel and maintain the lake quite low so that the subsequent and expected eruption will carry only a relatively small amount of water over the top of the crater.[4]

Regions of current and recent volcanism are of such interest that they are visited by thousands of people annually. The United States government, for example, has set aside several volcanic areas, such as Mauna Loa and vicinity in Hawaii, Mount Lassen in California, Crater Lake in Oregon, Mount Capulin in New Mexico, and the Craters of the Moon in Idaho, as national parks or monuments because of their educational and recreational values.

IGNEOUS INTRUSIONS

Extrusions of magma have been witnessed, but it is obviously impossible to witness an intrusion. The rock which lies between the top of the intrusion and the surface is known as the cover. This cover may be several miles in thickness, or it may, in extreme cases, be but a few feet thick. Intrusive rocks are not exposed until the forces of erosion (rock decay, wind, running water, and ice) have stripped off the cover. Of course, by the time the cover has been removed the magma has been solid for a long, long time. There are without doubt many igneous intrusions which have not yet been exposed by erosion, and in all probability some intrusions have been completely removed by deep erosion. To the geologist the earth's surface is not stable; it is constantly undergoing change, and the rocks which are exposed at one time differ from those exposed at another.

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[3] Zies, E. G., "Volcanoes and Human Geography": Pan-American Institute of Geography and History, Proc. Second General Assembly, Part III, Washington, 1935, pp. 328-336.

[4] Zies, E. G., "Surface manifestations of volcanic activity." Amer. Geophysical Union, Trans. 19th Ann. Mtg. Pt. 1, August, 1938, pp. 10-23.

The cover which separates the igneous intrusion from the surface acts as a blanket so that the magma cools more slowly than does lava at the surface. The length of time which it takes a magma to crystallize has a decided effect upon the size of the crystals or *texture* of the resultant igneous rock. Slow cooling, such as takes place in large igneous intrusions, permits the formation of mineral grains of visible size. Extruded magma cools so rapidly that the lava either solidifies as a glass or forms a rock composed of mineral grains of microscopic size. Of course a very thin intrusion may be chilled by the *country* (pre-existent) *rock* to such an extent that it assumes fine-grained texture similar to that of an extrusive rock.

Batholiths. The largest of the igneous intrusions are known as *batholiths.* Some are several hundreds of miles in length. Batholiths are so large that they are never sufficiently exposed to permit measurement of all three dimensions. In consequence there is some doubt as to their true shape. We know that most batholiths are much longer than they are wide and that many of them extend down to unknown depths. The typical batholith appears to enlarge downward, so that the deeper it has been exposed by erosion the greater will be its width and length. The upper surface is uneven, containing protuberances which are known as *cupolas* and depressions containing *roof pendants* of country rock (Fig. 120).

The Front Range of the Colorado Rockies contains a series of elongate north-south batholiths. Among these is the Pike's Peak batholith, a mass of granitic rock which includes not only Pike's Peak but also the surrounding mountainous area. A large batholith occurs in the Butte district of Montana, and another underlies most of central Idaho. The Sierra Nevada and Cascade ranges contain a large number of batholiths. New England and the southern Appalachians also have this same type of igneous intrusion. In fact, practically all granite occurs within a batholith.

You may wonder what happens to the rock that is in the way of an upward moving batholithic magma. Geologists differ on this point. Some believe that the batholithic magma as it moves upward pushes up and to one side the pre-existent rocks which are in its way, compressing and crumpling them at the same time. One sometimes finds that the country rock adjacent to batholiths is severely compressed and folded, but it is not always easy to prove that the force of the batholithic intrusion was responsible. Other geologists believe that the very hot magma moves upward by engulfing and subsequently dissolving large quantities of the rock in its path. The presence of partially dissolved fragments of roof rock within granite batholiths is cited to support this theory.

Contact metamorphism. As a magma cools, the various silicates which are dissolved within it crystallize until eventually the batholith becomes a solid mass of rock. The water and other fugitive elements which were present in the original magma do not appear in any abundance as components of the minerals produced by the crystallization, but escape from the magma during consolidation. Some enter the wall rock, causing *metamorphism* of that rock. Metamorphism means literally "change of form." Where caused by a magma it is called *contact metamorphism,* because the changes take place adjacent to the contact between the magma and the country rock. One result of contact metamorphism is the formation of new

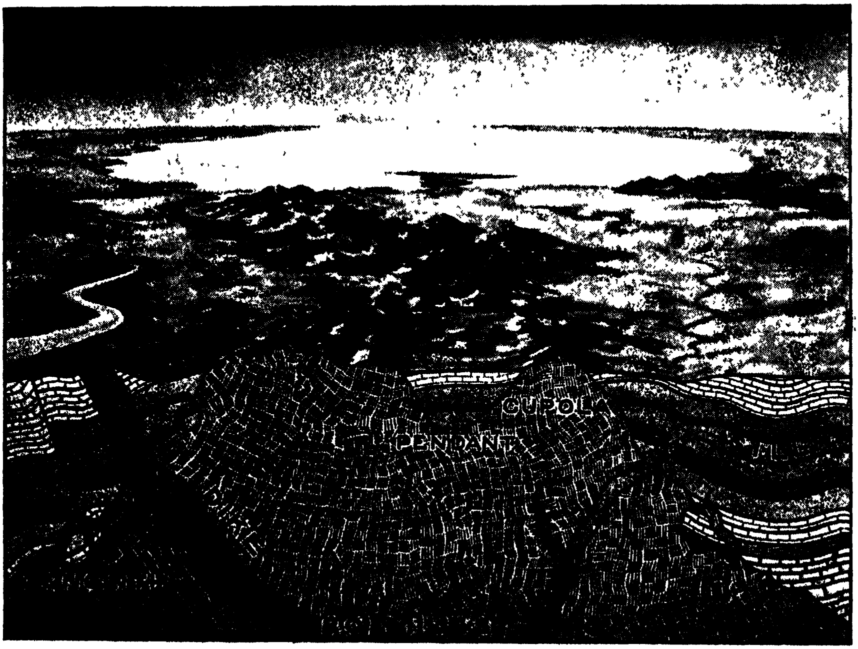

Fig. 120. Batholith intruded into sedimentary rock crust. After magma cooled and solidified, erosion stripped off most of the original cover. Roof pendant in center, cupola to right. Dike on left continues as dike through sedimentary layers, whereas dike on right becomes sill in sediments. Xenolithic fragments around borders. The area pictured is approximately 20 miles wide. *By John Jesse Hayes.*

minerals in the country rock through the deposition of fugitive materials. New minerals are also formed through the combination of fugitive elements with elements and compounds already present. A third effect is a mere recrystallization of the minerals already present in the country rock. Practically all igneous intrusions are surrounded by a zone of altered rock. Around a small shallow intrusive body, this contact metamorphic zone may be only a fraction of an inch thick; adjacent to a large deeply buried batholith it may exceed a half mile.

In some instances the fugitives, along with a considerable amount of not yet solidified magma, consolidate into separate irregular-shaped mineral deposits known as *pegmatites*. Pegmatites are famous

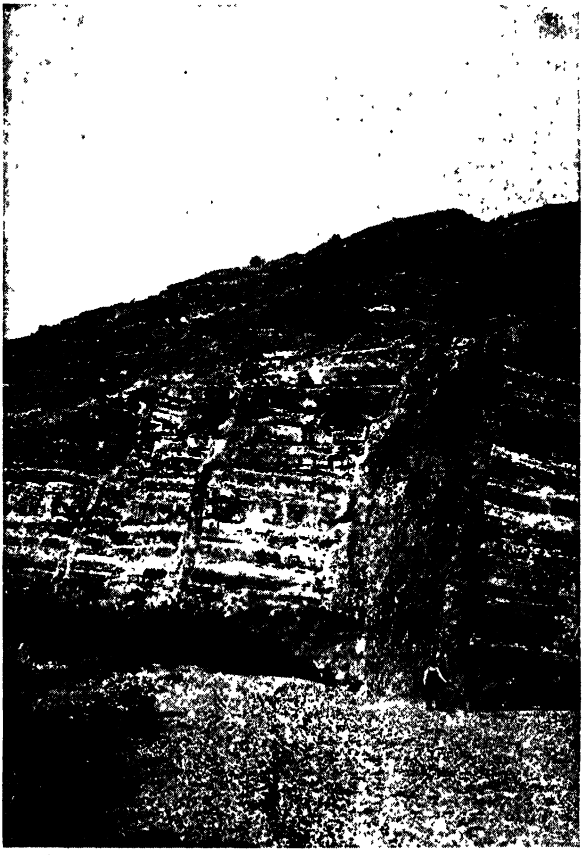

Fig. 121. Vertical dikes cutting near-horizontal sandstone layers. Alamillo Creek, New Mexico. *By N. H. Darton. Courtesy Geological Survey, U. S. Department of the Interior.*

for the great variety of rare minerals and the large crystals which they may contain.

Another possible course which the fugitive elements may follow is to escape surfaceward through cracks in the earth's crust. In this case the fugitive material consists mostly of water and is called a *hydrothermal* (hot water) *solution.* As these solutions move upward they encounter lower temperatures and various minerals precipitate, forming a *hydrothermal vein.*

Other types of intrusion. A *stock* is an igneous intrusion similar to a batholith, but smaller. Some of the igneous rock bodies which are called stocks may be cupolas of batholiths, and when erosion has removed the balance of the cover the entire surface of the batholith may become exposed.

A *dike* is a wall-like body of igneous rock (Fig. 121). It has a definite thickness, from a fraction of an inch to over a mile in exceptional cases. The length of a dike is much greater than its thickness (one dike is over a hundred miles in length). The third dimension, its depth, is usually unknown. Dikes may occupy any position between vertical and horizontal. Vertical and steeply dipping dikes, where harder than the surrounding rock, make prominent ridges at the surface. Dikes of this type radiate from the Spanish Peaks in Colo-

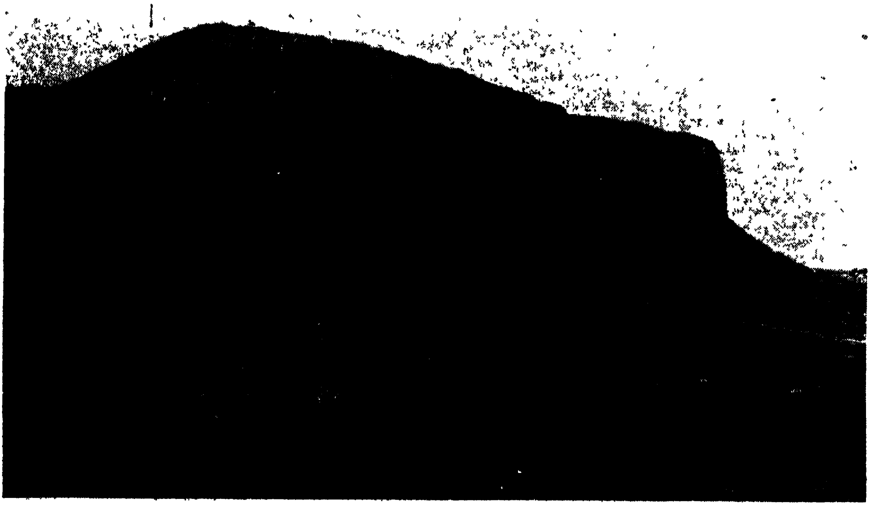

Fig. 122. Igneous sill, Drumadoon, Island of Arran, located in Firth of Clyde, Scotland. Overlying rock beneath which sill was intruded has been removed by erosion; underlying conformable sediments visible at left. Columnar jointing of igneous rock is characteristic. ***Courtesy Geological Survey and Museum, London.***

rado (Fig. 39). In some localities the dike rock is softer than the intruded rock, in which case it will erode faster and produce a trench. The only qualification other than shape which a dike must meet is that where it intrudes layered rock it must cut across the layers. A flat body of igneous rock that is intruded between layers or bands is called a *sill* (Fig 122). Sills likewise may occupy any position between horizontal and vertical, depending entirely upon the dip of the layered rock. Most sills are but a few feet in thickness, but in exceptional instances they exceed a thousand feet.

An igneous intrusion that lies between rock layers, but which has a mushroom shape so that the overlying layers are arched, is called a *laccolith* (Fig. 123). The Henry Mountains of southern Utah contain laccoliths that have been uncovered by erosion. Several dome-like occurrences of stratified (layered) rock in the Black Hills of South Dakota are thought to be underlain by laccolithic intrusions.

The lava which builds a volcano comes up through the earth's

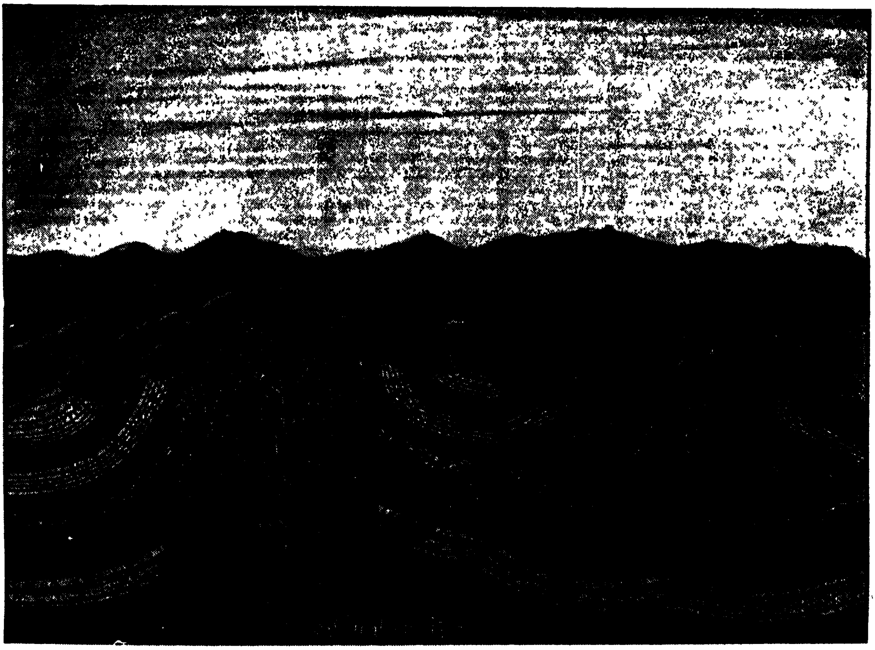

Fig. 123. Stock and laccolith. The arching of the overlying strata is characteristic of the laccolith. The drawing covers an area approximately 5 miles wide. *By John Jesse Hayes.*

crust in a pipe-like conduit known as a *volcanic neck* or *plug* (Figs. 124 and 125). When the volcanic activity ceases the magma filling the neck solidifies. Although it was on its way to become extrusive rock this igneous material is intrusive in its relationship to the surrounding rock. Erosion may subsequently destroy the entire cone, but the rock within the neck extends downward to unknown depths as evidence of a former period of volcanism.

Mineral deposits. According to modern geologic thought, the source of all matter, including the atmosphere surrounding the earth, the water lying upon the earth, and the rock composing the earth, is the magma. Naturally, therefore, the magma is also considered to be the primary source of ore minerals. Evidence for this theory has been found by many individuals and in many localities. Scientists have collected and analyzed samples of the gases given off by volcanoes. Such gases come directly from the magma

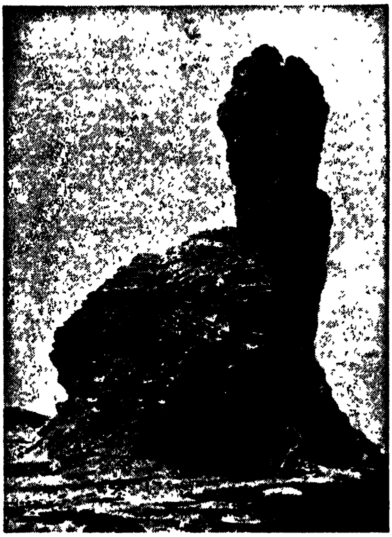

Fig. 124. The Rock and Spindle, St. Andrews, Fife. Vertical mass (the "Rock") is volcanic neck. "Spindle" or spinning wheel is radial mass of columnar basalt which apparently resulted from the injection of lava into cavity opening off volcanic chimney. *Courtesy Geological Survey and Museum, London.*

and therefore give factual evidence of the composition of this liquid. Water vapor is the most abundant constituent of volcanic gases. Some, but not all, of this water may be surface and ground water that has filtered downward and joined the magma. Also present are chlorine, fluorine, gaseous oxides of carbon and sulphur, nitrogen, boron, and many other elements and compounds.

Coincident with or following the great explosion that blew the top off Mount Katmai in Alaska in 1912, a near-by valley became partially filled with hot igneous rock through which steam escaped from a multitude of vents. This place was named the Valley of Ten Thousand Smokes by the first visitor. Scientists visiting the valley while the steam was still escaping in considerable magnitude found that minerals, some of which contained metals, were being formed around the vents of these "blow-outs" or fumaroles. This is direct evidence of the presence of metallic elements in magma. In addition, analyses of igneous rocks show the presence of metals. In most instances the metallic minerals are in very small, but widely distributed, grains. A microscopic examination of many rocks will

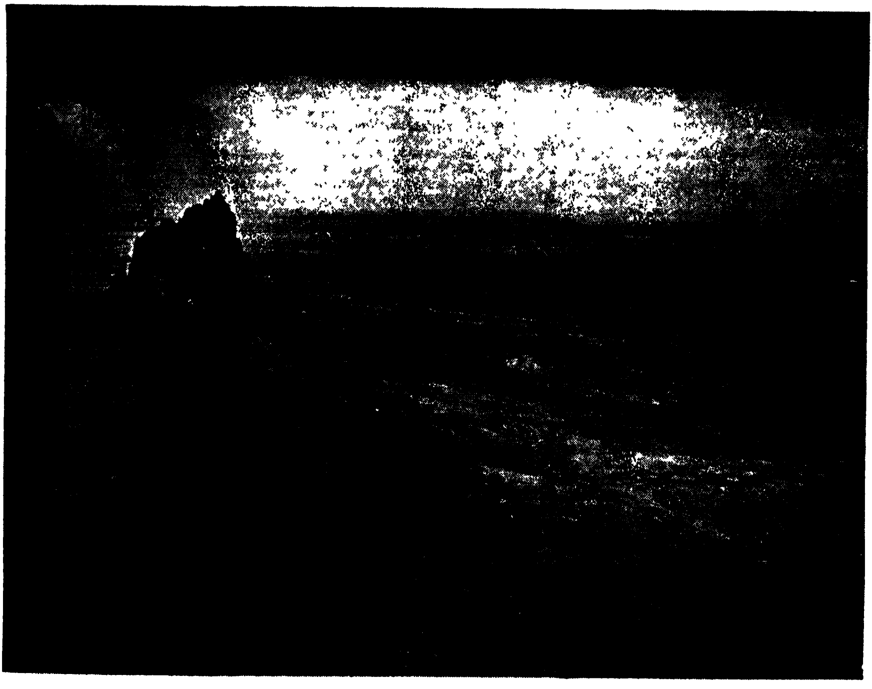

Fig. 125. Eroded volcanic neck with radial igneous dike. Ship Rock, New Mexico. *By permission Spence Air Photos.*

reveal the presence of iron as the sulphide, pyrite, or as the oxide, magnetite. Granite in a few localities, especially in South Africa, contain scattered crystals of tin ore. Pegmatites, which are formed from concentrated residual magmatic "juices," may contain ores of tin and tungsten and, in noncommercial amounts, many other metallic minerals including even gold.

Finally, there is the close relationship found in most districts between igneous rocks and ore deposits. Ore deposits do exist in regions where no igneous rocks are exposed, but such occurrences are exceptional. Most of the mining of primary ore minerals takes place in regions of large-scale igneous activity.

It is not meant to be implied that all ore deposits as at present constituted are of immediate igneous origin. Many great ore bodies, including most of the commercial iron deposits, are *secondary,* the metals originally deposited through igneous activity having undergone subsequent transformations through the geologic processes which take place at and near the earth's surface.

CLASSIFICATION OF INTRUSIVE IGNEOUS ORE DEPOSITS

A. Magmatic deposits
B. Pegmatites
C. Hydrothermal deposits

A varying degree of relationship with the parent magma distinguishes each of these three groups. The first type includes ore deposits which are found within the source magma, in which case the relationship between the two is unmistakable. The same is true of the second type, for pegmatites result from the crystallization of special magma which are derived from larger normal magmas. However, the source magmas for hydrothermal veins, the most common of the primary ore deposits, lie at such depths that the relationship between the two is one of inference rather than of direct observation in most instances.

Most economic geologists believe that the metals occurring in veins came from a crystallizing magma within the earth's crust, and that they were carried upward either by water likewise given off by the crystallizing magma, or by ground water that mixed with the igneous emanations and picked up the metallic compounds.

Magmatic deposits. Certain types of ores characteristically occur within sills and other igneous rock bodies. The containing rocks consist dominantly of dark-colored silicate minerals.

Certain iron, titanium, nickel, and chromium ore minerals are found in this environment. It was originally believed that these deposits were due to a process known as *gravitative differentiation,* which means that, as a magma crystallizes, the heavy minerals (which include the ores) sink to the bottom, and the lighter minerals rise to the top, so that when solidification is complete the rock exhibits a rude "stratification" according to the specific gravity of the component minerals. However, more detailed studies of these ore bodies have demonstrated that in some cases, at least, the ore minerals formed later than the other minerals in the rock and so could not have become concentrated by sinking to the bottom of a slowly crystallizing magma. But the association of these ore minerals with the enclosing rock is so general one must conclude that they are very closely related.

Diamonds occur almost invariably in dark rocks composed mostly of the mineral olivine. The crystals, about 25 percent of which are of gem quality, are rather indiscriminately scattered through the "mother rock." The South African diamonds occur in vertical pipes, circular or elliptical in outline, which range from 50 feet to one-half mile in diameter. These pipes are the throats or conduits of volcanoes that have been completely removed by erosion. The rock in the pipe is the lava that congealed when volcanic activity ceased. It is dark-colored ("blue ground") except at and near the surface where weathering processes have transformed it to soft and incoherent "yellow ground." The principal discoveries in recent years have been of rich placer fields. These now yield more diamonds annually than do the pipes.

Ore minerals are also found scattered through igneous rock bodies in most cases in insufficient concentration to be exploitable. For example, certain dark-colored igneous rocks may contain scattered grains of native platinum which through erosion of the rock become concentrated into workable placer deposits in the stream beds. Sulphides of copper, oxides of iron, and tin ore may likewise be scattered through igneous rocks in non-commercial amounts.

Pegmatites. The normal crystallization of an intrusive magma results in the formation of an igneous rock such as a granite. However, the minerals in the resultant rock do not use all of the elements present in the magma, and those that are used may not be removed in the same proportions that existed in the original magma. Consequently, deep within a crystallizing batholith will be a much smaller mass of residual liquid composed not only of the dominant elements present in the original magma, but also of those elements which were originally present and which, not having been removed through crystallization, are relatively concentrated. This residual liquid is without doubt highly aqueous, because water is one of the "rejected" compounds. The crystallization of the very fluid, residual magma produces a pegmatite (see Fig. 126). Solidification may take place in the interior of the batholith where the residual magma accumulates, or fracturing of the batholith due to continued cooling with consequent contraction may permit the escape of the pegmatite magma to distant points before solidification takes place.

From a commercial standpoint, the pegamatites are more important as sources of non-metals, such as feldspar and mica, than of metallic minerals, However, some commercial deposits of tin and a few of tungsten ore occur in pegmatites.

Hydrothermal deposits. Most primary ore deposits are hydrothermal in origin. Some of these are *disseminations,* with the ore minerals scattered widely through the enclosing rock. Perhaps the best examples of this are the so-called *"porphyry copper"*

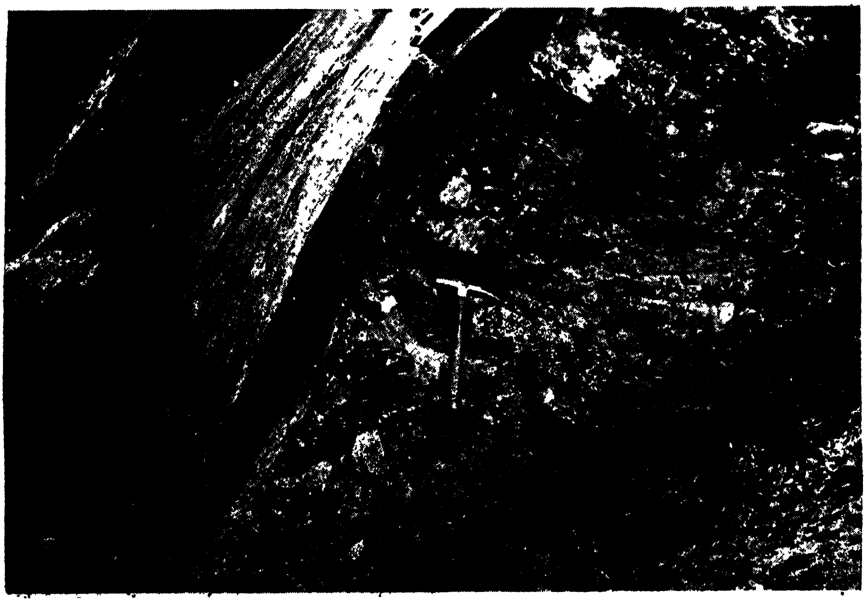

Fig. 126. Contact between country rock (left) and pegmatite. Mica books abundant in border zone of pegmatite, especially above hammer. *By D. B. Sterrett. Courtesy Geological Survey, U. S. Department of the Interior.*

deposits, as at Bingham Canyon, Utah. There the small grains of copper-containing minerals are disseminated through a great hill of rock, all of which is being removed by mining (Fig. 127). Of more common occurrence are hydrothermal *veins*. Such well known ore bodies as the Mother Lode of California, the copper deposits of Butte and the Lake Superior region, the gold and silver ores of the Cordilleran belt, and the fairly recently discovered rich deposits of the precious metals in Ontario and Quebec fall into this classification.

Veins have not always been considered to be of igneous origin. Such deposits have been mined from earliest times, and naturally scientists have theorized as to how the *ore* (valuable) and *gangue* (valueless) minerals became concentrated in veins. One of the early theories was that these minerals precipitated from a universal sea and worked their way downward into cracks and fissures which extended from the sea floor into the underlying rocks for great distances. This somewhat naive explanation was succeeded by one with considerably more scientific logic behind it, the theory of *lateral secretion*. According to this theory, metals originally dis-

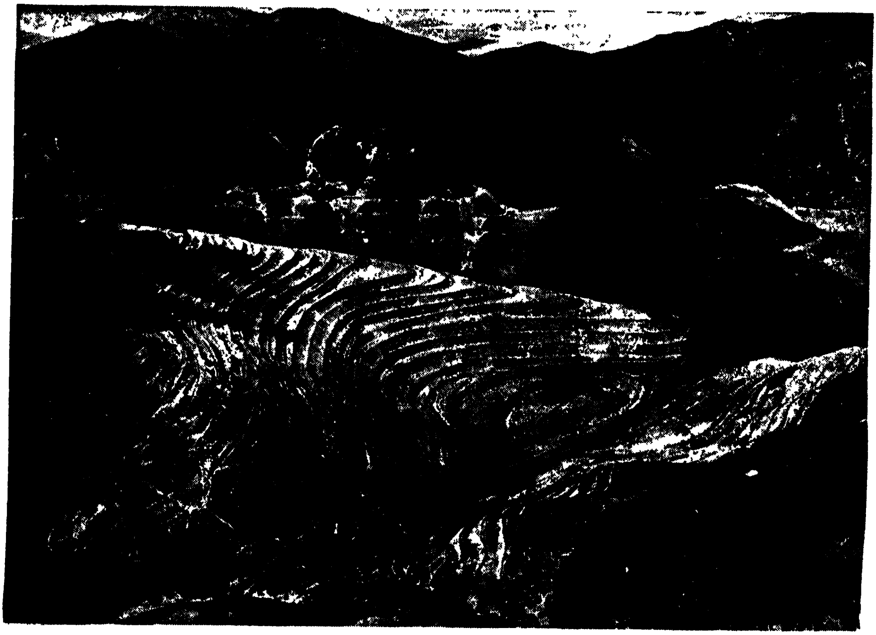

Fig. 127. Open cut copper mine, Bingham Canyon, Utah. *By permission Spence Air Photos.*

seminated throughout the rocks in the earth's crust are picked up by circulating ground waters and redeposited in concentrated form in fissures. The lateral secretionists were not able, however, to produce any evidence that the rocks within any reasonable distance of the vein had been leached of any metallic constituents. On the contrary, it appears obvious that the wall rocks of many veins have been enriched by solutions escaping outward from the fissures.

The concept of mineral deposition by hot solutions which come up from deep-seated igneous intrusions was originally evolved by a French geologist in the middle of the last century. The theory gained a following in the United States and other countries early in the present century and since then has steadily increased in favor. Now there are but few primary ore deposits which are not considered by economic geologists to be of hydrothermal (igneous) origin. It is believed that toward the close of magma crystallization the residual liquid consists dominantly of water, and that concentrated in this water is the greater part of the metalliferous content of the original magma. Eventually these hydrothermal solutions break loose and move surfaceward, taking advantage of cracks formed through cooling and contraction, fault fissures, and any other openings that may be present. As the waters move upward they enter zones of lower temperatures and pressures. These factors, especially the former, cause precipitation of minerals, because the solubility of most substances decreases with decreased temperature and pressure. Another factor that may cause minerals to precipitate from ascending hydrothermal waters is the mingling of solutions, such as magmatic waters with ground waters, so that chemical reactions follow which produce insoluble compounds. Hydrothermal solutions may also react with minerals in the wall rock so as to produce insoluble compounds. For this reason some veins show a noticeable change in mineral content where they pass through different types of wall rock. Lessened pressure as the surface is approached permits the escape of gases in solution in the magmatic waters, and the loss of these gases diminishes the solvent power of the waters.

Because of the rock pressures existing at depth, the cracks through which hydrothermal solutions move surfaceward are extremely narrow. However, the solutions themselves are probably under sufficient pressure to force the walls apart, thereby making room for additional minerals to be precipitated. Furthermore, many veins have been widened by a process of *replacement* (Fig. 128), the upward surging solutions dissolving the wall rock bordering the vein and depositing minerals in the space thus made available.

Other avenues of migration, besides cracks formed through cooling and contraction, and fissures created by faulting, are open to the hydrothermal solutions. Joint cracks formed by diastrophic activity are abundant, especially in the upper parts of the earth's crust. Buried lavas may be vesicular at their upper surface, in which case opportunity is afforded mineralizing solutions to travel through the vesicles or gas bubble holes. Such channelways were utilized by solutions depositing native copper in the Lake Superior district. Both in the Lake Superior district and elsewhere solutions have traveled through the pores of incompletely cemented sandstones and conglomerates, just as ground waters migrate through those openings.

A vein is a tabular body with one definite dimension, its thickness, and two indefinite dimensions, length and depth. Some veins are less than an inch in thickness, many are several feet from wall to wall, and a few are as much as a hundred feet, or more. The thickness of a vein is quite likely to vary from place to place, swelling

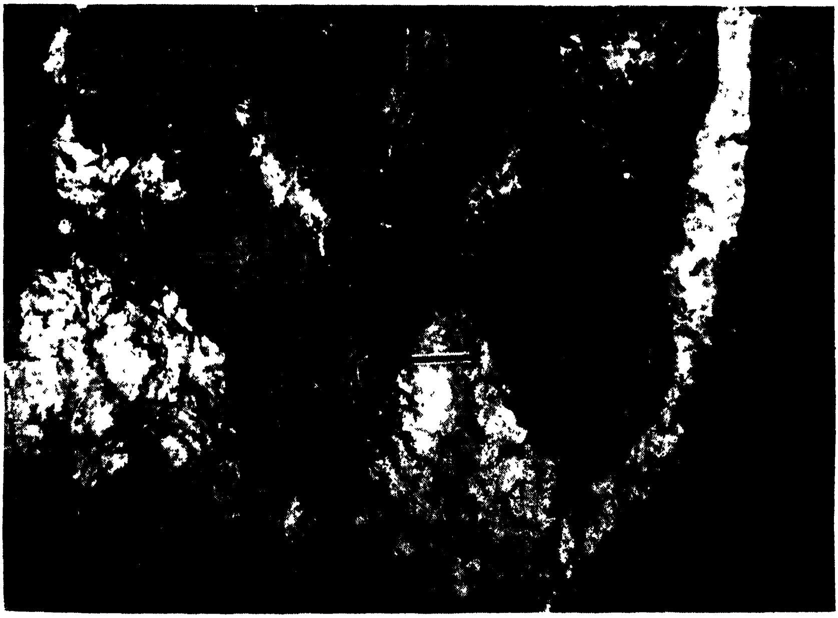

Fig. 128. Gold quartz vein (white) which has emplaced itself by replacing the preexisting rock. Scale is 6 inches long. Homestake Mine, 3050-foot level, Lead, South Dakota. ***Courtesy Homestake Mining Company.***

and pinching noticeably, and perhaps even lensing or tapering out altogether. This is especially true of replacement veins, wherein the thickness varies with the vulnerability of the wall rock.

Some veins are typically banded, the minerals being arranged in parallel fashion conformable to the vein walls. Veins may split into branches and in some instances the branches rejoin again. A system of veins roughly parallel to each other and occupying a restricted zone is known as a *lode.*

Most veins are steeply dipping or vertical (Fig. 129). A few veins are traceable along the outcrop for many miles, but in most instances they disappear in a relatively short distance. There is likely to be much more persistence in depth, although the ore values may not continue downward consistently.

Gangue minerals usually occur much more abundantly than ore minerals in veins. In some gold deposits the gold is invisible to the naked eye and the vein appears to be composed of gangue only. The commonest associates of gold are quartz and pyrite. Lead occurs in hydrothermal veins as the sulphide, galena. Some mines exploit veins containing silver-bearing galena and so produce both

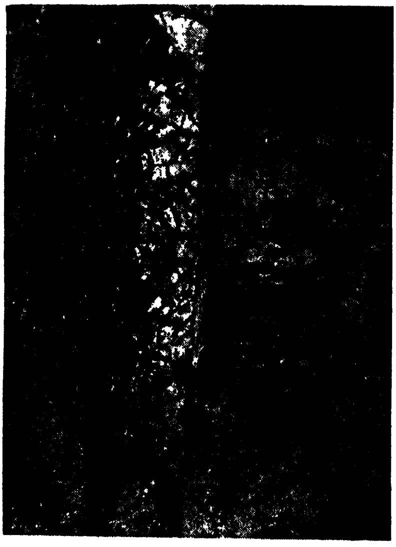

Fig. 129. Vertical vein containing brecciated quartz. Empire Mine, Alaska. *By W. D. Johnston. Courtesy Geological Survey, U. S. Department of the Interior.*

lead and silver. Another associate of galena is sphalerite (zinc ore), and where both minerals are present lead, zinc, and even silver may be marketed. Veins cutting Keweenaw Point of Lake Superior contain native copper and gangue, but in most other parts of the world copper is combined with sulphur and perhaps iron. Other important veins are those containing tin and tungsten minerals.

Iron is an exception among metals in that its ore minerals do not occur in commercial amounts in veins. More iron is usually present than gold, copper, lead, or zinc in the veins that are exploited, but this metal is elsewhere so abundant and consequently so cheap that it does not pay to extract it from the vein deposits.

Economic geologists classify ore veins into low, intermediate, and high temperature types according to the characteristic assemblage of minerals formed under different temperature conditions. They have also been able to identify different zones in mineralized regions because of the varying character of the ore deposits at different distances from the source magma. This in itself is very strong evidence in support of the theory of the igneous origin of ore deposits.

VARIETIES OF IGNEOUS ROCK

Classification. Rocks of igneous origin differ from each other in physical character, texture, and mineral composition. The first two of these properties depend largely upon the environment in which the magma consolidated to form igneous rock, the third upon the chemical composition of the magma. All igneous material falls naturally into three classes, which differ from each other in physical character. These classes are separately discussed in the following paragraphs.

Unconsolidated igneous rocks. Included here in the fragmental material which is ejected into the air by volcanoes. *Volcanic ash, pumice, cinders, and bombs,* all of which were described earlier in the chapter, are examples. The percentage of igneous rock in the earth's crust consisting of unconsolidated material is insignificant. This type is largely confined in its occurrence to the cones of explosive volcanoes; only the ash is ever carried any great distance from the volcanic vent. Pumice and volcanic ash deposits are mined, and the material is used for scouring and polishing purposes.

Natural rock glass. Magmas are solutions; a sudden chilling prevents the precipitation of any of the dissolved compounds so a solid solution, or glass, is the result. Some unconsolidated igneous rocks, such as volcanic ash and pumice, are glass, because of the sudden chilling of magma erupted into the air. In rare cases, lava poured out onto the earth's surface has cooled so rapidly that it has been turned to glass. Commonest of the natural glasses is *obsidian,* a dark rock that transmits light through thin edges. Obsidian occurs in a thick massive body at Obsidian Cliff, Yellowstone National Park. This material was prized highly by the American Indian; arrowheads made of Yellowstone obsidian are found in many places far distant from the Park.

Solid crystalline rocks. By far the greatest number of igneous rocks falls into the third group, which includes all solid crystalline rocks, even though the individual crystals may be microscopic in size. Texture and mineral composition are used to subdivide the rocks falling within this group. Lava flows and thin dikes and sills cool so rapidly that the crystals which form are microscopic in size. This texture is known as *dense.* Rocks which cool more slowly (as in batholiths) range from *fine* to *coarse* in texture. They contain crystals of visible size, and the mineral content of the rock can therefore be determined without recourse to a microscope. Some magmas move into a new position after crystallization has commenced, and this change in environment may cause the not-yet-crystallized magma to cool rapidly so that the older and larger crystals become surrounded by crystals of much smaller size. Such a texture is called *porphyritic,* and the rock is referred to as a *porphyry.*

The most abundant mineral in igneous rocks is feldspar. Most of the light-colored igneous rocks also contain quartz. These are said to be *acidic* in composition. The dark-colored or *basic*[4] rocks contain little or no quartz; instead they consist dominantly of feldspar and black or dark green minerals rich in iron and magnesium such as augite, hornblende, and olivine. Mica, magnetite, and pyrite may be present in minor amounts in any of these rocks.

A highly simplified chart is given below showing the positions of four varieties of igneous rock. The two most abundant types are in capital letters.

It should be noted that rhyolite and granite have the same minerals and, therefore, the same chemical composition. Obviously, then, a chemically similar magma produces both rocks; the type is depen-

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[4] The terms "acidic" and "basic" applied to rocks refer to their relative silica content and not to their chemical radicals.

Texture	Composition	
	Acidic Consist dominantly of feldspar and quartz and consequently are light in color.	*Basic* Consist dominantly of feldspar and dark-colored minerals (such as augite, hornblende, and olivine).
Dense	Rhyolite	BASALT
Coarse	GRANITE	Gabbro

dent solely upon the rate of cooling. Likewise the one magma (chemically different, however, from the granite-rhyolite magma) will produce either basalt or gabbro, depending upon the environment at the time of consolidation. As a general rule, the dense rocks are extrusive in origin, and the coarse rocks occur in igneous intrusions.

Gradations occur, both vertically and horizontally, in the chart. Between the dense and the coarse rocks are the porphyries. A rhyolite porphyry consists of visible crystals set in a dense *groundmass* of invisible (microscopic) crystals; a granite porphyry contains very large crystals interspersed with smaller, but still visible crystals.

Between the rhyolite-granite and the basalt-gabbro families are several other similar rock families. Most of these are classified as *intermediate,* because they lie between the acidic and basic rocks in composition. Complete gradation exists between rhyolite, the intermediate extrusive rocks, and basalt; and between granite, the intermediate intrusive rocks, and gabbro. Of minor quantitative importance, the intermediate rocks are of great economic significance, for the magmas that produce them also supply the hydrothermal solutions from which veins of gold, silver, copper, and other metals are precipitated. Still more basic than basalt and gabbro are *ultra-basic* rocks. These occur only in coarsely crystalline intrusions; volcanic equivalents of the ultra-basic rocks are unknown. An example is *peridotite,* a dark green or black rock composed largely of the mineral olivine. Most of the world's diamonds, platinum, nickel, and asbestos occur in or associated with peridotite.

The commonest acidic rock is granite, which is intrusive in type, whereas the most abundant basic rock is basalt, a lava. This curious condition is probably due to the fact that a basalt-gabbro magma has high liquidity, therefore its chances for penetrating through the crust and flowing out on the surface are much greater than they are for the highly viscous granite-rhyolite magma.

Rhyolite. Rhyolite is a light-colored dense rock. Most or all of its crystals are of microscopic size; they interlock to form a very tough rock. Because rhyolites grade into rhyolite porphyries, visible crystals of feldspar, quartz, and mica may occur scattered through the rock. The greatest thickness of rhyolite flows in the United States is in Yellowstone Park, and the Grand Canyon of the Yellowstone River is cut into this rock.

Granite. The most abundant rock in the continental crust of the earth is granite, which occurs mainly in batholiths. This rock consists of a tight granular aggregate of visible crystals of quartz and feldspar, with such accessory minerals as mica or hornblende also present in relatively minor amounts. Granites may be white, gray, pink, red, or green, depending in most cases upon the color of the feldspar, which is the dominant mineral. Masses of granite are exposed in many parts of the world, especially in mountainous regions, and in northeastern North America and northwestern Europe.

Granite is a very popular building stone and is so used in many parts of the world. Its greatest use in this country, however, is for monumental stone.

Basalt. Our great lava flows, such as those forming the Columbia Plateau of northwestern United States, are composed of basalt, a dark-colored, heavy, dense rock; the ingredient crystals are all of microscopic size in most cases. Basalt occurring at the top of a lava flow may be vesicular or scoriaceous due to the escape of dissolved gas at the time of consolidation. Ordinarily, however, basalt is exceptionally tough and durable, properties which prevent its use as a building stone because of the expense of dressing (cutting and polishing) it. Basalt (usually under the name "trap rock") is crushed and used for road surfacing and in concrete aggregate.

Gabbro. Gabbro is a relatively uncommon intrusive igneous rock. It is as coarse as granite; the crystals of feldspar, augite, olivine, and other minerals which are present but invisible in basalt are large enough to be recognizable in gabbro. The color, black or nearly so, is due to the abundance of dark-colored iron and magnesium minerals in the rock.

CHAPTER 11

Diastrophism and Its Effects

DIASTROPHISM INCLUDES ALL MOVEMENTS of the earth's crust. This geologic process has had a dominant rôle in making the continents habitable by mankind. For example, diastrophism has helped to create harbors and mountains, and has made deposits of coal, oil, salt and other mineral products available to us. If crustal movements were to cease (a highly improbable concept), the continents would eventually be worn down to near sea level, after which attack by the oceans might destroy them altogether.

Evidences of diastrophism. Physiographic evidence for diastrophism was given in Chapter 8, where shorelines of emergence and submergence were described. Other testimony for fluctuations of sea level is also available. We know, for example, that certain land areas have risen since the dawn of civilization. Docks on the island of Crete, which were constructed long ago by ancestors of the present inhabitants, are now high and dry. In some places rocks which in former times were submerged and a menace to navigation now stand above the sea, even during highest tides. Many coral reefs, which must have been built beneath the surface of the water, extend well above sea level. Precise measurements made by competent surveyors and repeated every few years show that changes have taken place in the elevation of various parts of the world. The Scandinavian Peninsula, for example, is rising at the rate of about two and one-half feet per century.

There is also evidence that some areas are sinking. Buildings which were obviously constructed near the shore, but above the reach of the tides, have in some instances become partially submerged. In a few localities roads can be seen running down to the present shore line and on out beneath the water. Recent encroachments of the sea have inundated forests.

Although evidence for recent crustal movements is most easily obtained along shorelines where the ocean surface provides a plane of reference, such movements are by no means confined to the edges of the continents. Earthquakes furnish spectacular proof that diastrophism is taking place wherever such tremors occur, and no region of any size is immune from quakes. Neither are the evidences of diastrophism restricted to the recent past. We have ample proof of earth movements far back into the geological past. Sedimentary rocks which were deposited beneath the ocean surface are to be found on all continents and at all elevations. Diastrophism caused the elevation of these sediments to their present position. Furthermore, more than one cycle of submergence, followed by uplift, is involved in almost every instance. Marine sediments may be interbedded with strata of continental origin. Each alternation means a submergence, with deposition of sediments in marine waters, followed by emergence and deposition of fresh-water or wind-blown materials. There have been countless oscillations during geologic history which caused huge sections of continents to alternate between a submergent and emergent condition.

Other evidences of diastrophism include the presence of rocks which have been folded and faulted (broken), or which have been changed (metamorphosed) as a direct or indirect result of crustal movement. These and other results of diastrophism, such as earthquakes and mountains, will be discussed in subsequent parts of this chapter.

CAUSES OF DIASTROPHISM

No one knows for certain why the earth's crust moves. The action is no doubt initiated beneath the crust, where investigation of causes is hindered by inaccessibility. Several theories have been advanced to explain diastrophism; the most acceptable of these is that the interior of the earth is shrinking, and movements of the crust are due to sporadic adjustments of this outer shell over a continuously contracting underlying sphere. The earth may be contracting due to cooling, for rock material shrinks in volume as its temperature is lowered. One hypothesis of earth's origin is that our globe was first a great body of gas, which cooled and contracted into a sphere of liquid magma. This continued to cool, and the magma gradually solidified, producing our planet as it now exists. The escape of further heat from the interior of the earth would be accompanied by shrinkage of the cooling rocks beneath the crust.

It is believed that the loading of a part of the earth's crust with a great thickness of sediment will cause that part to sink. At the same time the crustal segments from the surfaces of which the sediment was removed will be made lighter, and will tend to rise. If this is true, deltas and other regions of concentrated deposition are negative (sinking) elements in the earth's crust, and mountains and high plateaus, where erosion is most active, are positive (rising) elements. A subcrustal flowage of rock from beneath the sinking segments to beneath the rising segments must also be postulated. This *theory of isostasy* (Chapter 7) has considerable evidence to support it. Isostasy can be used to explain some of the vertical movements of the earth's crust.

PROCESSES OF DIASTROPHISM

Vertical movements. Upward and downward movements of parts of the earth's crust have been the rule rather than the exception in the geologic past. Evidence for this has already been given; it includes not only the alternation of marine and continental strata among outcropping sedimentary rocks, but also the elevated or depressed character of many shore lines. These vertical movements were probably no more rapid than the movements taking place today. A sinking or rising of but two and one-half feet a century, the rate of movement on the Scandinavian Peninsula at the present time, would amount to nearly 5 miles in a million years, and past geologic time involves many millions of years.

Large-scale vertical movements, such as those in which whole continents move up or down, are caused by the sinking or rising of great blocks of the earth's crust. Movement over a much smaller area may be produced by the intrusion of magma into the rocks of the crust, or by other movement of magma, as when lava is drawn from a reservoir in the crust and extruded upon the surface. Even the compaction of compressible rocks, as takes place when a clay is converted into a shale, will be accompanied by downward movement (settling) of the overlying rocks.

Vertical movements are by no means confined to simple upward or downward motion, for evidence of tilting is found in many places. Some tilting may have been caused by an uplift of the crust at one point and a depression at another, (as in a teeter-totter), but other tilting was no doubt due to different rates of uplift or downsinking at different points. Elevated shoreline beaches, which obviously were horizontal when formed, are found in some localities to have a noticeable inclination in one direction or another. Tilting on a large scale is shown by the eastern shoreline of the United States. The northern part of this shoreline is marked by numerous bays, which are signs of submergence, while the south Atlantic coast has very few harbors and numerous barrier beaches (Chapter 8) which are characteristic of emergent coasts.

Although no region is immune from diastrophism, the greatest movements have taken place within belts of crustal weakness which are, or have been occupied by mountain chains. One type of local deformation is *warping*. An area may be down-warped into a basin or up-warped into a broad dome. Of great importance in the geologic past have been very elongate down-warps known as geosynclines. Ordinarily these down-warps are of sufficient magnitude to permit the ocean to enter. Streams flowing into submerged geosynclines bring in sediment from surrounding land areas which accumulates in considerable thickness as the geosyncline continues to sink. In this way sedimentary strata thousands of feet thick may be deposited in water which at no time is very deep, so that the marine organisms (later to become fossils) which are entrapped within the sediments are all of a relatively shallow-water type.

Horizontal movements. Segments of the earth's crust may move in a horizontal direction as well as vertically. At any one point the forces acting horizontally may produce *compression* or *tension*, depending upon whether the segments are being forced toward or away from each other. Wherever rocks in the earth's crust are subjected to compressive forces they become *folded*. Folds may be very small "wrinkles" or, where the compression was intense, huge pleats in the crust of the earth. In some instances the rock fails to hold together during compression and breaks with one segment sliding up over the other. This is known as faulting. Faulting may also be produced by tension in the earth's crust, but in this case one segment, instead of overriding the other, will slip down on it. Folds and faults will be considered in more detail in the following section on the results of diastrophism.

Tension on a relatively small scale is created by the cooling and contraction of igneous rock after it consolidates. This causes the rock to crack, producing fissures known as *joints*. Joints produced by contraction, and from other causes, are also described in the following section.

RESULTS OF DIASTROPHISM

One result of diastrophism is the changed shoreline produced by either submergence or emergence of coastal areas. Elevated sea cliffs and beaches, bays, and fiords, and several other shoreline features (Chapter 8) are produced by vertical movements of the earth's crust along the edges of the continents. Another result of diastrophism, mentioned earlier in the chapter, is the presence of sedimentary rocks of marine origin above sea level. However, the *continental masses,* or *platforms,* and the *ocean basins* have been stable features throughout traceable geologic time. Practically no sedimentary rock which was deposited at abyssal depths is exposed at the surface. Likewise, it is doubtful if any appreciable part of the oceanic basins of today ever formed continent masses. The continental platforms stand many thousands of feet above the bottoms of the ocean basins (but not above sea level). Depressing such a platform a few hundred feet would permit the ocean waters to inundate vast portions of the continent, but at the same time it would not destroy the relative relationship of the continental mass with respect to the surrounding ocean basins. In other words, the seas which encroached upon the continents owing to diastrophic movements were relatively shallow *epicontinental* ("upon the continent") rather than abyssal seas. Hudson Bay is an epicontinental sea of today, and an uplift of the North American continent of a few hundred feet would drain this huge bay.

Other results of diastrophism, such as rock structures, earthquakes, mountains, and metamorphism, are discussed separately in the remaining pages of this chapter.

ROCK STRUCTURES

The form and position of a body of rock determines its structure. Some structures, such as stratification, cross-bedding, and mud cracks, are *original;* they were created before the lithifaction of the rock. Other rock structures, such as folds and faults, came into existence during or *after* the lithifaction of a sedimentary rock or the consolidation of an igneous rock. Millions of years may elapse between the time of formation of a rock and the period of diastrophism which creates structures of this type. The study of the form and position of rocks is called *structural geology;* this branch of the science is used to obtain a picture of what lies beneath the rocks exposed at the earth's surface.

Joints. A critical examination of the rocks exposed at the surface reveals a number of features that are caused by movements of the earth's crust. One such feature to be observed is *jointing* (Fig. 130). A joint is a crack or fissure in the rock which forms without any displacement, with respect to each other, of the rocks on the opposite sides of the crack. An important cause of jointing is the tension (tendency to pull apart) which rocks may undergo during diastrophism. This tension may be relieved by jointing along numerous planes perpendicular to the direction of force. The settling of brittle rocks, such as limestones and sandstones, over an uneven surface will also create tensions which will cause jointing. Such uneven surface may be produced by the compaction of an underlying shale which was deposited around and above hills, or which contains within it lenses (discontinuous beds) of relatively incompressible material, such as sand. Where buried hills or bodies of sand occur, the compaction of the shale will be less, and overlying brittle beds cannot bend over these higher points without cracking. The vibrations in the earth's crust caused by earthquakes are probably another important cause of rock jointing.

Diastrophism also produces compression which may cause the

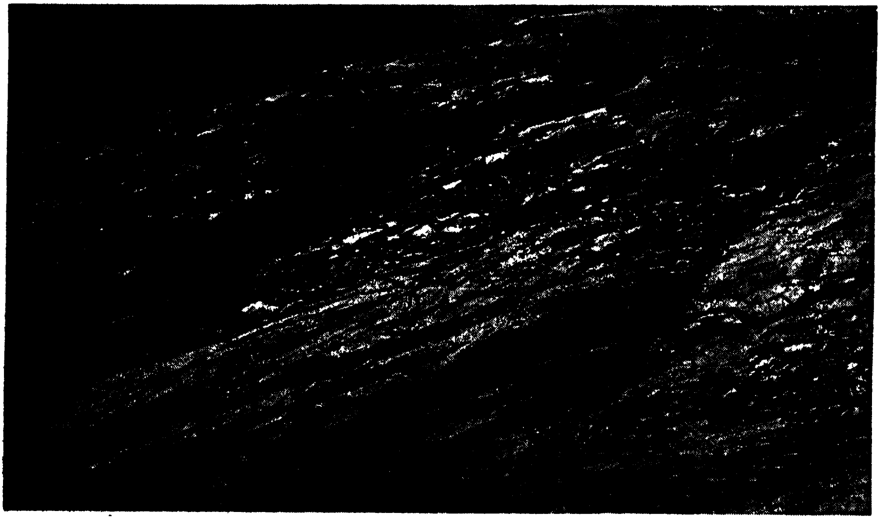

Fig. 130. Sheet (near-horizontal) jointing in granite. Treasure Mountain, Gunnison County, Colorado. ***By J. W. Vanderwilt. Courtesy Geological Survey, U. S. Department of the Interior.***

rocks to crack along *shear planes,* which are joints inclined 45 degrees to the direction of force. The cooling and contraction of igneous rocks, and the dehydration and consequent contraction of sediments, likewise produce joints.

Joints are very common in hard (brittle) rocks. They generally occur in three systems of parallel planes, of which two are vertical, or nearly so, and the third horizontal. In many cases the vertical joints intersect each other at such angles as to produce a diamond-shaped pattern on the surface. Theoretically, fissures can extend downward for a distance of 10 or 12 miles, but increased rock pressure with depth narrows the opening between the walls of a joint. As a matter of fact many deep mines are dry in the lower levels, because the fissure walls at those depths are squeezed so closely together that water does not have adequate space in which to flow.

Joint cracks may be filled with water, with air, or other fluid, or with minerals precipitated by percolating waters. Weathering debris accumulates in these fissures, but in most instances such material is not packed sufficiently tight to prevent the movement of air and water through the cracks.

Joints are of considerable importance to mankind. The quarryman both loses and gains by the presence of these natural rock fractures. If the joints are too close together he cannot quarry dimension stone; if they are too far apart his blasting costs may be excessive. Surface water becomes ground water by percolating down joint cracks and furnishes the entire underground supply where sandstones and other porous rocks are absent. Near Cañon City, Colorado, oil is obtained from fissures (joints) in shale. Ore veins may occupy joint cracks which originally extended deep into the earth and were utilized as channelways by upward-moving solutions.

Tilted rocks. Another result of diastrophism is the tilting of rock masses (Fig. 131), readily observable where the rocks are stratified. Ordinarily, sedimentary layers are deposited in a horizontal or near-horizontal position. Exceptions occur where the marine floor on which deposition took place was inclined, as on the outward end of a delta. With this exception the presence of tilted rocks is evidence that diastrophism has taken place, causing one part of the crust to be pushed up in respect to another part. The geologist designates the exact position of a tilted rock stratum by means of *strike* and *dip.*

The determination of strike and dip is not difficult. One must consider two planes, one the plane of the inclined rock stratum and the other the plane of the horizontal. These two planes will intersect along a straight line, as will any two planes that are not parallel. This straight line is the strike. Because one of the planes is horizontal, the strike line will also be horizontal, so its direction can be designated in terms of the points of the compass. We speak of an inclined bed as striking east and west, or striking north 47 degrees west, or striking in some other compass direction. If the surface of the ground is horizontal, the cross-country trend of the outcrop of an inclined rock stratum will parallel the strike. The dip is the vertical angle between the plane of the dipping rock and the plane of the horizontal. The *direction* of the dip is at right angles to the strike. For every strike two dip directions are possible, unless the strata are vertical.

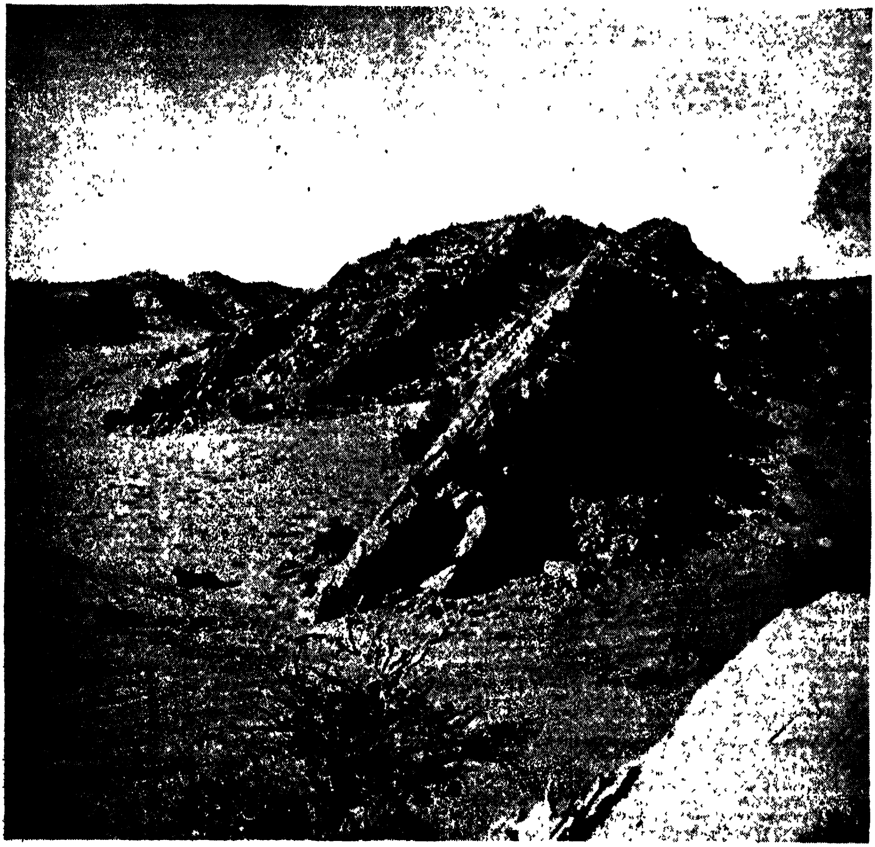

Fig. 131. Hogbacks made by tilted Dakota and younger sandstones east of Gallup, New Mexico. Team and buckboard at lower left give scale. *By N. H. Darton. Courtesy Geological Survey, U. S. Department of the Interior.*

The symbol which is used on maps to designate the strike and dip of rocks is Y 37°. The plain line shows by its direction the strike of the rocks. The arrow line shows the direction of dip, and the figure gives the degree of dip.

The investigation of the inclination of rocks is an important part in searching for oil, coal, and other mineral deposits.

Folds. Inclined strata are usually the limbs of *folds.* There are many types of folds. Where the stratified rocks are bowed upward, the fold is known as an *anticline* (Fig. 132). A downward fold is called a *syncline.* If the stratified rocks are bent in one direction only, the fold is known as a *monocline* (Fig. 133). An anticline which is circular in plan like a trench helmet is called a *dome.* A circular syncline is called a *basin.* Most anticlines and synclines are elliptical, like a canoe. They vary greatly in magnitude; some are but a few feet across, and in others the dimensions may be a matter of miles (Figs. 134, 135, 136, 137 and 138). Very large folds contain superimposed minor folds. Many anticlines and synclines lie side by side, so that the flank of one is also the flank of the other.

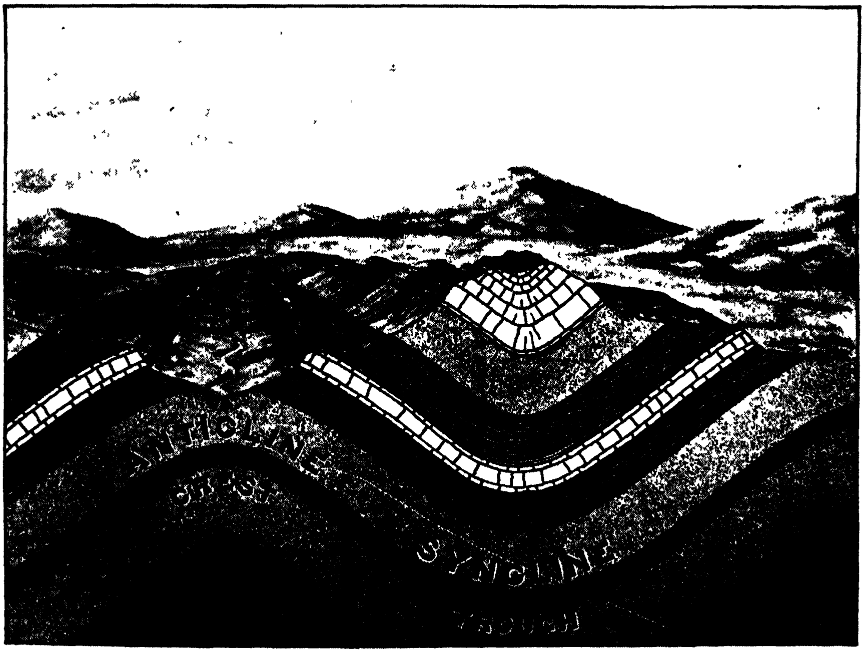

Fig. 132. Upfold or anticline bordered by a downfold or syncline. The character of the fold is not reflected in the surface topography; an anticline is just as liable to be a valley (as shown above) as a ridge. *By John Jesse Hayes.*

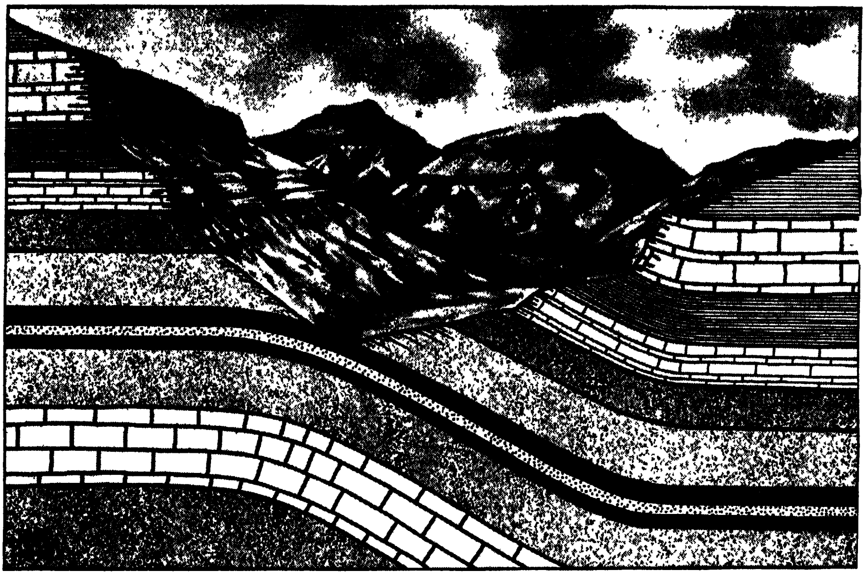

Fig. 133. Terrace fold or monocline. Again there is no connection between the character of the fold and the topographic form. *By John Jesse Hayes.*

Fig. 134. Anticline exposed in shore cliff. Most anticlines are much too large to be visible in a single photograph. Folded Coal Measures at Saundersfoot, Pembrokeshire. ***Courtesy Geological Survey and Museum, London.***

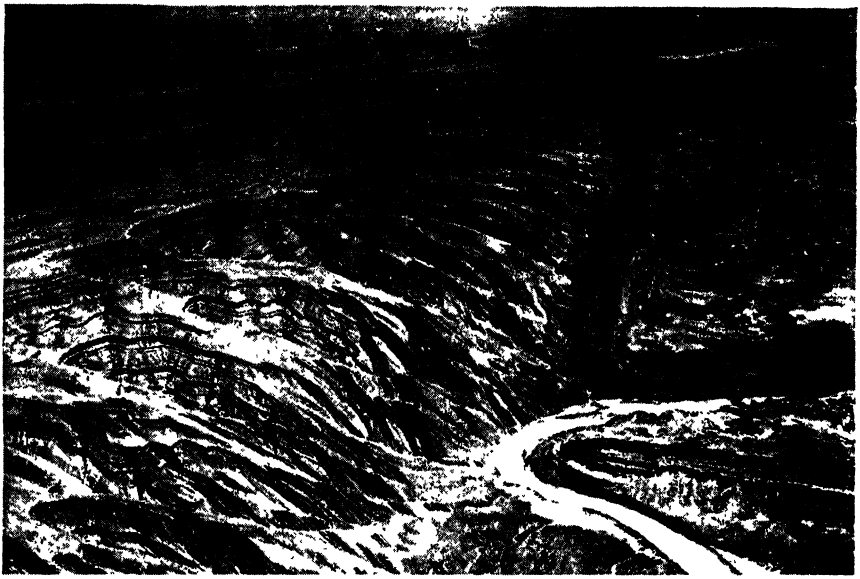

Fig. 135. South limb of eastward plunging anticline north of San Juan River, Utah. Southerly dip visible in exposures in tributary draws; flat lying sediments at upper end of draws are on axis of anticline. *By permission Spence Air Photos.*

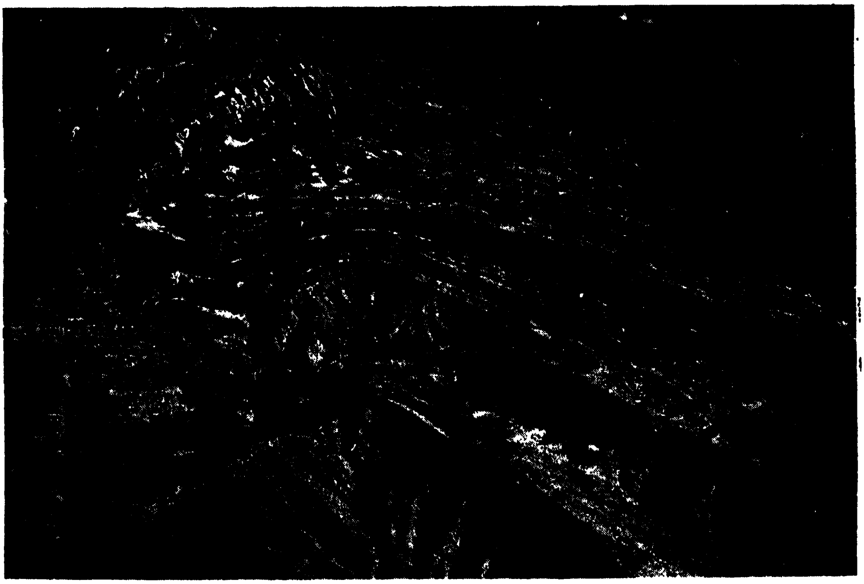

Fig. 136. Dissected anticlinal ridge north of Ojai, Ventura County, California. *By permission Spence Air Photos.*

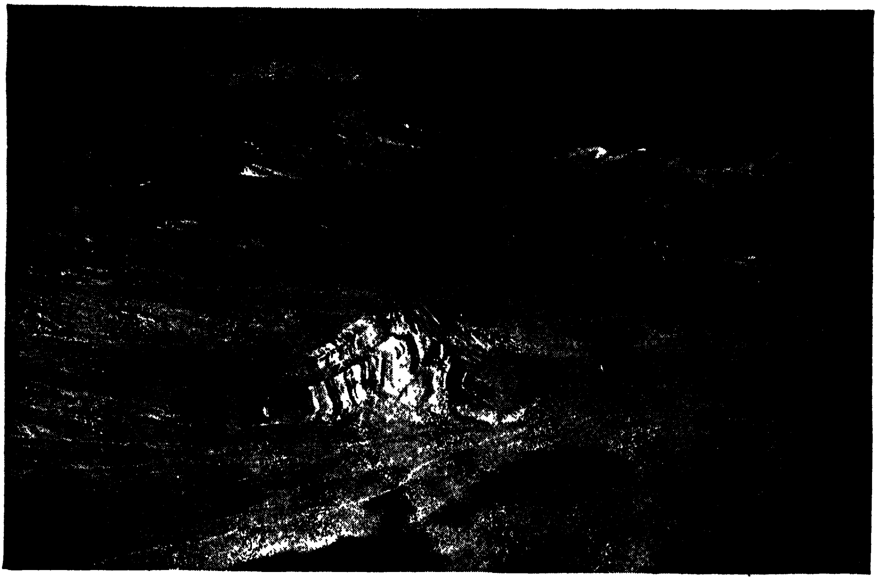

Fig. 137. Folded limestone of Carboniferous age in Butte Valley, Panamint Range in Inyo County, California. *By permission Spence Air Photos.*

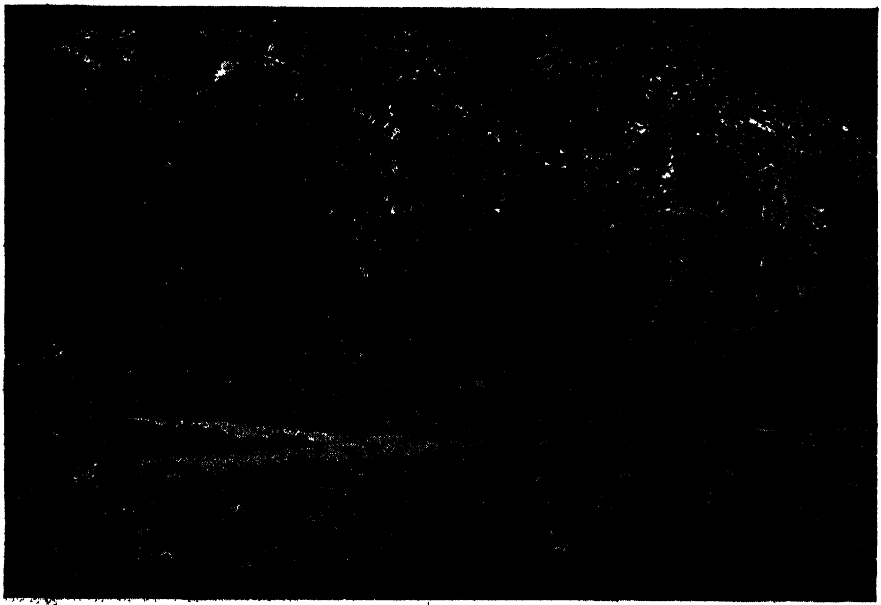

Fig. 138. Folded Triassic limestone and shale, Copper Creek, Alaska. *By F. H. Moffit. Courtesy Geological Survey, U. S. Department of the Interior.*

Anticlines and synclines are not necessarily hills and valleys on the earth's surface. In many instances valleys occur along the axes of anticlines, and the rocks outcropping near the center of synclines may form mountain ridges. Ordinarily the diastrophism which causes folding is so slow that the agents of erosion are able to keep the surface fairly well smoothed off while the folding is taking place. At any rate, the time *since* folding took place has been sufficiently long in most cases to cause the obliteration of whatever topographic effect the folding itself may have caused. But folding does produce tilted rocks, and, if the various layers are of unequal hardness, differential erosion will create hogbacks (Chapter 5). A region of folded rocks can be recognized in many instances by the distinctive topography, consisting of parallel hogbacks, with inter-

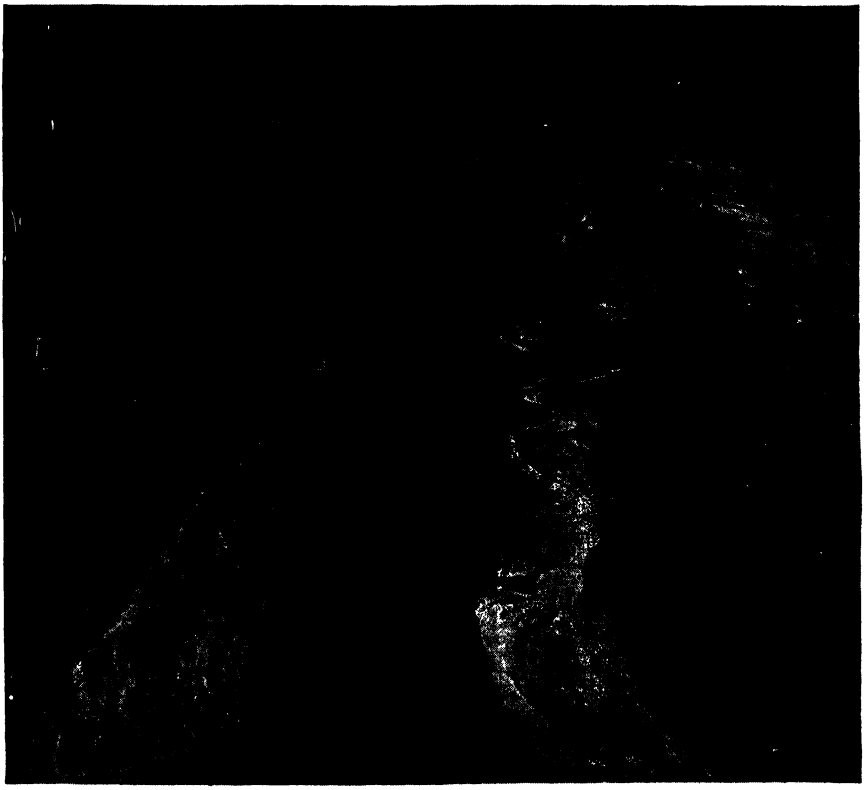

Fig. 139. Hogback on flank of anticline. Slope to right (east) from summit of hogback is the dip slope. Stream has carved its valley along outcrop of less resistant rock and is therefore subsequent. Comb Ridge, Utah. *By permission Spence Air Photos.*

vening valleys, and a trellis drainage pattern. The trend of the hogback ridges is approximately parallel to the strike of the rock formations, and the slope of the cap rock of each hogback gives the local dip (Fig. 139).

Faults. Where the diastrophic forces are greater than the rocks can withstand by stretching or compressing, the rocks break and a *fault* is produced. A fault differs from a joint in that the rocks on the two sides of the fracture have suffered relative displacement (Fig. 140). The plane of the fracture is known as the *fault surface.* The outcrop of a fault surface is referred to as the *fault line.* Ordinarily fault planes are not vertical but are steeply inclined. The rock bordering the fault plane on the upper side is called the *hanging wall,* that on the under side the *foot wall.*

Faults cause segments of the earth's crust to move *vertically, laterally,* or *both vertically and laterally.* Some faults are caused by tension in the crust of the earth. This stress is relieved by fracturing, with the rocks on one side of the break slipping down with respect to those on the other. This is called a *normal fault;* the hanging

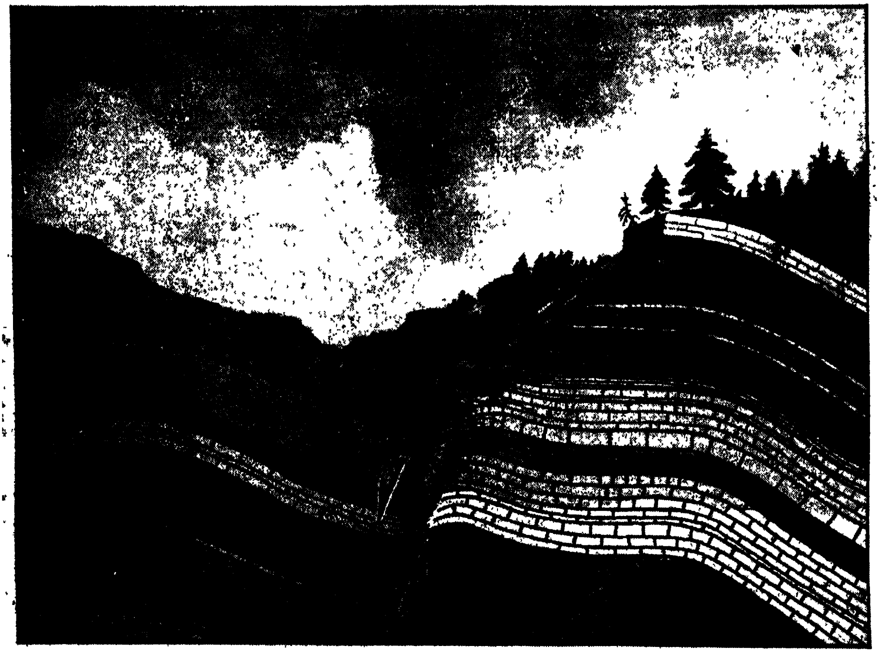

Fig. 140. Normal fault. Hanging wall (left) side has moved down in respect to footwall side. Cliff at upper right is fault-line scarp; stream along fault line is a common phenomenon. ***By John Jesse Hayes.***

wall moves down the fault plane from its former position. If the rocks are subjected to compression instead of tension, the resultant faulting differs in that the rocks on one side of the fault will ride up on those on the other side, thereby shortening the distance between points on opposite sides of the fault. This is known as a *reverse fault;* the hanging wall side of the fault moves up with respect to the foot wall (Fig. 141). Compression or tension in the rocks is relieved sometimes by a series of parallel faults, called a *fault zone,* instead of by a single fault. Another type of compound faulting consists of two parallel faults with the intervening rock dropped down, forming what is known as a *graben* (from the German word for *ditch*). If the intervening block of rock is shoved up (or remains up while the adjacent rock sinks) a *horst* is produced (Fig. 142).

The amount of *displacement,* or distance between two points on

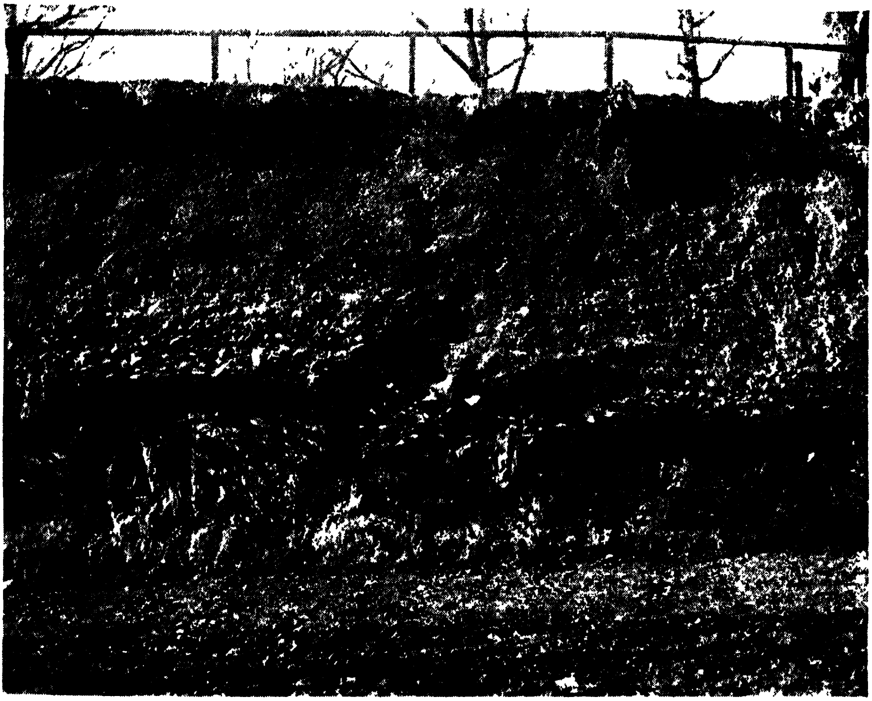

Fig. 141. Reverse fault in schist overlain by terrace gravels. Fault plane is visible in left center of picture, dipping steeply from right to left. As is the rule in reverse faulting the movement has placed older rock (the schist) directly above younger rock (terrace gravels) which abuts the fault plane. Rock Creek, Washington, D. C. *By N. H. Darton. Courtesy Geological Survey, U. S. Department of the Interior.*

opposite sides of a fault which were formerly contiguous, varies greatly. Some faults are little more than joint cracks, with displacements of a fraction of an inch, whereas other faults have displacements measurable in feet and even in miles. Movements of from ten to fifty feet are very common, and in mountainous regions many faults have displacements of several hundred to several thousand feet. Where faulting cuts across sedimentary rocks it is often possible to identify the strata on opposite sides of the fault surface and to measure the amount of the displacement with considerable accuracy. The determination of the length of the fault line may be difficult because of the presence of soil and alluvium masking the outcrop. By interpolating between exposures where necessary, some fault lines have been traced for many miles. An extreme case is the San Andreas fault in California which has been mapped for over 500 miles (Fig. 143). Movement along this fault plane caused the earthquake of 1906.

Faulting is one of the few geologic processes that is preponder-

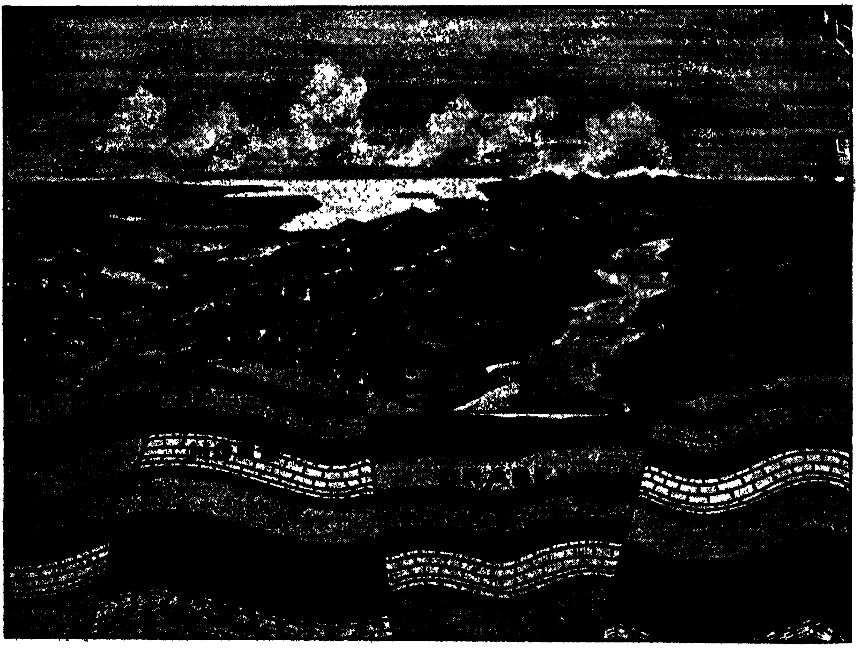

Fig. 142. Horst, or upfaulted block, bordered by downfaulted grabens. Block faulting of this type produces the "basin and range" topography found in parts of Utah and Nevada, and the "rift" valleys which occur in central Africa. *By John Jesse Hayes.*

antly sudden and in some instances catastrophic. When faulting occurs, an earthquake results. Fault planes behave as safety valves in the earth's crust. When the diastrophic stresses get to be more than the rocks can stand, faulting occurs. Movement may occur many times on the same fault plane. Geologists refer to faults as being "dead" when there is no evidence of any movement. Others are "live"; they have been active in recent times and quite logically may be expected to be active again. However, faults are something like volcanoes; we can never be absolutely sure when they have ceased to be active.

The results of faulting are many. Some are very local in nature, confined to the immediate vicinity of the fault. The rocks adjacent to the fault plane may be rubbed together with such pressure that they become pulverized and are converted into a sort of clay, known as *fault gouge.* If the rock adjacent to the fault is broken into angular fragments instead of being pulverized, a *fault breccia* results. The rock along the fault plane may be scratched or grooved during the movement. These striations, known as *slickensides,* are valuable

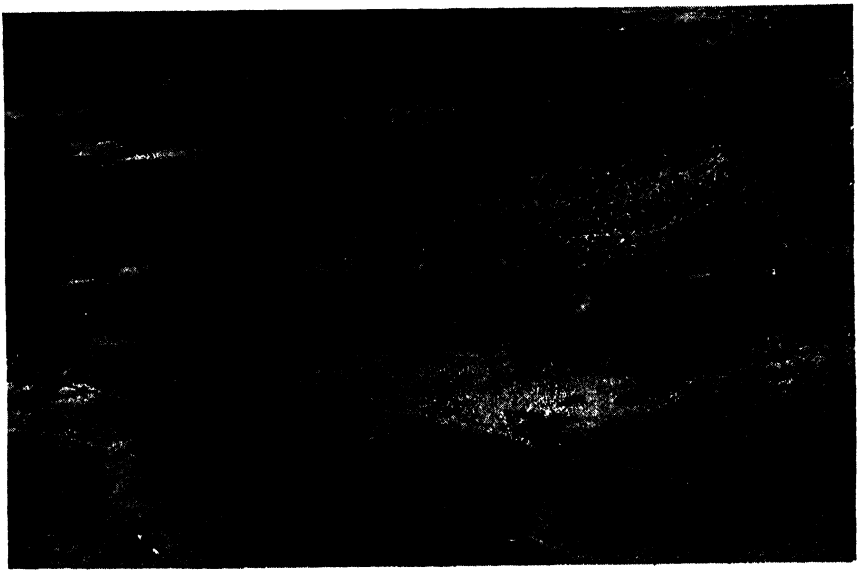

Fig. 143. San Andreas fault passing through Indio Hills, California. Fault line crosses center of picture (lower right of center to upper left of center). Major movement along fault plane was in horizontal direction; left (west) side of fault moved away from camera, shifting flats at lower right to left center and bringing into view hills at lower center which were originally back of camera. *By permission Spence Air Photos.*

in that they give direct evidence as to the direction in which the movement took place. In the case of stratified rock, the beds next to the fault plane may be bent in the direction in which the movement took place. This is known as *drag,* and is likewise important in giving evidence of the direction of movement.

Other results of faulting are the abrupt truncation of rock layers at the fault plane and the bringing together of rocks which were not previously in contact. Reverse faulting causes older rocks to overlie younger, which is contrary to the usual order, and may prevent some rocks from outcropping although they may be present beneath the surface. Normal faults may cause repetition of outcropping strata. Lateral movements on the fault plane, and vertical movements in tilted strata where the fault line does not parallel the strike of the rocks, cause an *offset* of the outcropping rocks.

Faulting in some instances has a decided effect on the surface topography. Vertical movements produce cliffs at the surface which

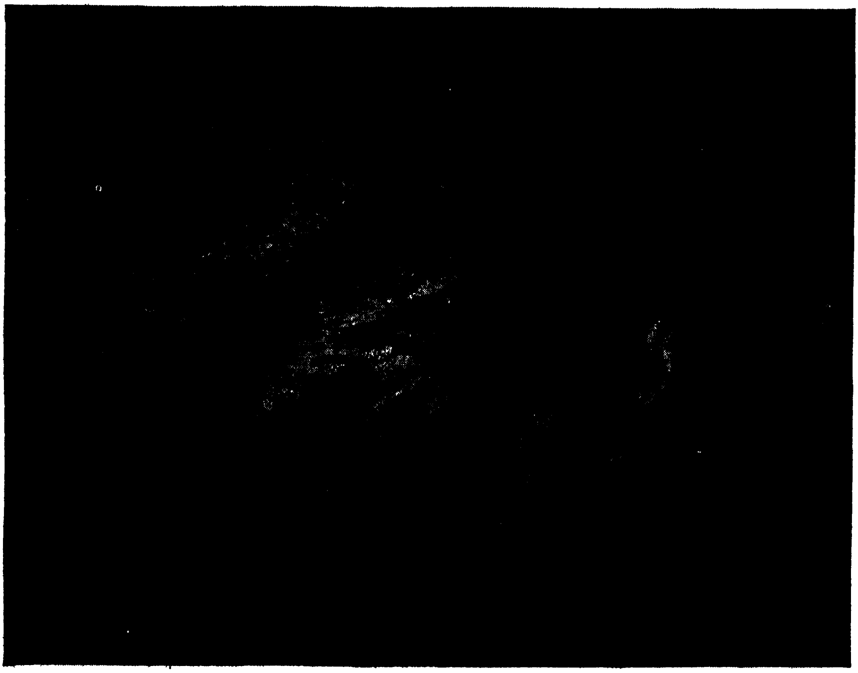

Fig. 144. Prominent fault scarp on MacDonald Lake (near Great Slave Lake), Northwest Territory, Canada. Early Precambrian granite to left has been faulted up so that it lies alongside Middle Precambrian sediments. ***Royal Canadian Air Force photograph. By permission Department of National Defense, Ottawa, Canada.***

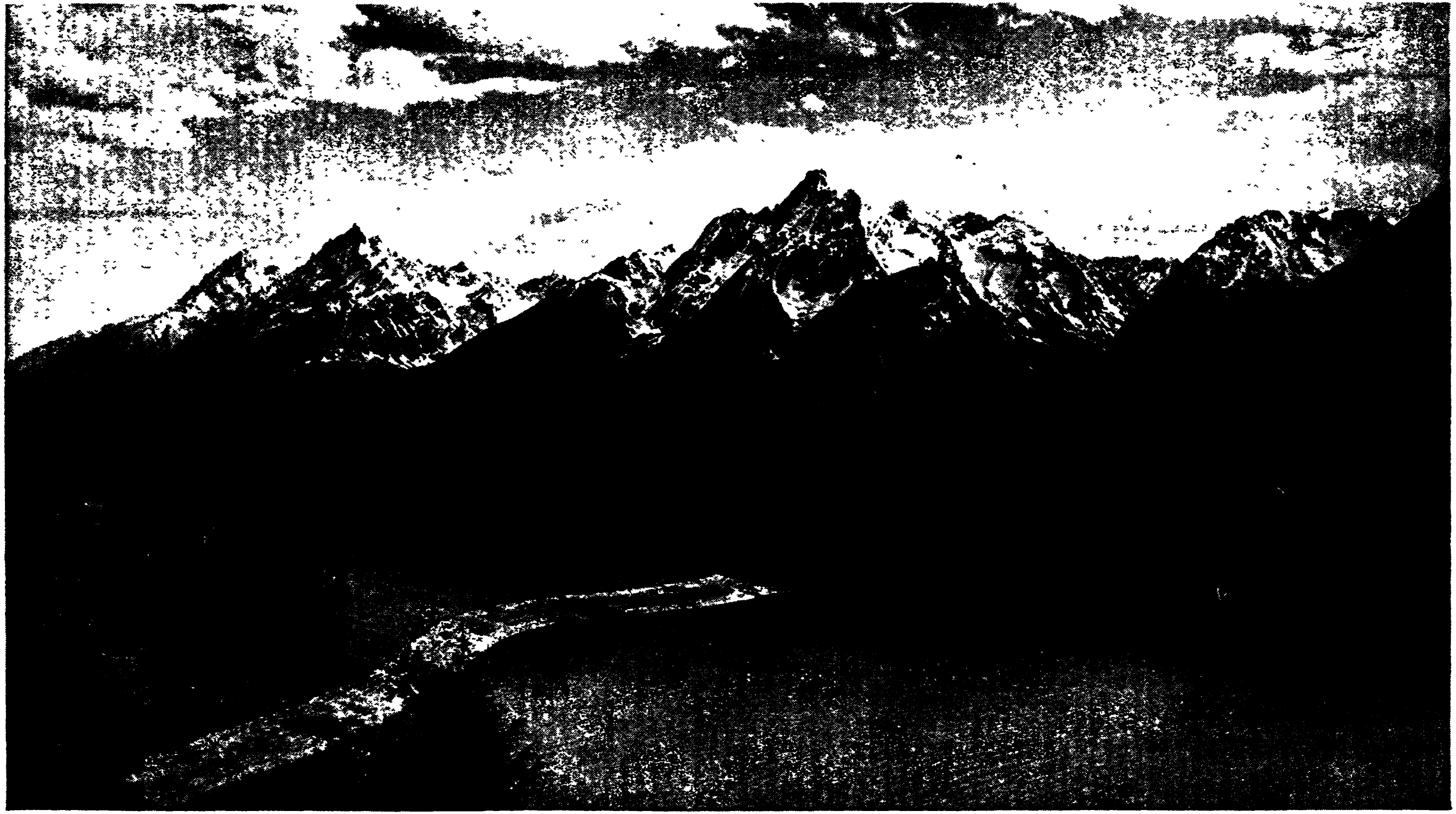

Fig. 145. Fault-line scarp forming east wall of upfaulted Teton Range. Jackson Lake in foreground. Grand Teton National Park, Wyoming. *By George A. Grant. Courtesy National Park Service.*

are called *fault scarps* (Fig. 144). These scarps are relatively short-lived because they are attacked by the forces of erosion and planed off so that the surface on the "up" side of the fault line becomes level with the surface of the ground on the "down" side. However, when this is done, rock of unequal resistance to erosion may be exposed on opposite sides of the fault line. The softer rock will be eroded faster (regardless of whether it was initially on the "up" side or the "down" side of the fault), and a cliff will again be formed along the line of the fault. This type of scarp, created by differential erosion, is known as a *fault-line scarp* (Fig. 145).

The rock adjacent to a fault plane is in many cases so broken up that the forces of erosion can excavate it with relative ease. A large number of fault lines are occupied by stream valleys. Eccentricities in the courses of rivers flowing through faulted regions are due to the streams' following fault lines over parts of their courses. Some down-faulted blocks (grabens) are occupied by rivers or elongate lakes. The Rhine River of Germany flows through a graben valley over part of its course. The depression occupied by the Red Sea is a graben. The below-sea-level elevation of Death Valley in California is due to the fact that it too is a graben.

Faulting has a number of economic effects. The miner, whether he is working a coal bed or an ore vein, constantly gets in trouble in a faulted region through running into faults and losing the bed or vein. He must work out the structural geology in detail before he knows in what direction to mine in order to pick up the coal seam or ore body across the fault. On the other hand, some fault planes and zones were used by ore-depositing solutions as channelways and as a result are themselves occupied by valuable ore deposits.

Live faults present a distinct hazard in engineering construction. A dam, aqueduct, canal, or other feature built across a fault line could be destroyed by a renewal of movement. Steps taken to prevent such catastrophes are discussed in Chapter 18.

Fault planes and zones are in many instances used as channels by circulating underground waters. Faults can be traced on the surface in some districts by the presence of a series of springs along the fault line.

Unconformities. Strata which are deposited one upon the other on the sea floor without interruption are said to be *conformable*. If, however, there is a period of emergence between two periods of submergence, the contact between the sediments deposited during the two submergences is called an *unconformity*. There are several types of unconformities. If tilting or folding occurred subsequent to the earlier deposition but before the younger sediments were laid down, the younger, overlying beds will not be parallel to the older strata (Frontispiece). This is spoken of as an *angular unconformity* (Fig. 146). If there was no tilting or folding, but if the older rocks while exposed at the surface were eroded into hills and valleys so that the contact is a wavy one, it is called an *erosional unconformity* or *disconformity* (Fig. 147). The strata above and below an unconformity of this type are parallel. In some unconformities there is no physical evidence of an emergence between the deposition of two series of strata, but discrepancies in the ages of the contained fossils show a time break. Unconformities are of material aid in unravelling geologic history, for they constitute a record of past submergences, emergences, and other types of diastrophism.

EARTHQUAKES

If Mother Earth kept a diary, she would record over one thousand earthquakes during the course of an average day. About half of

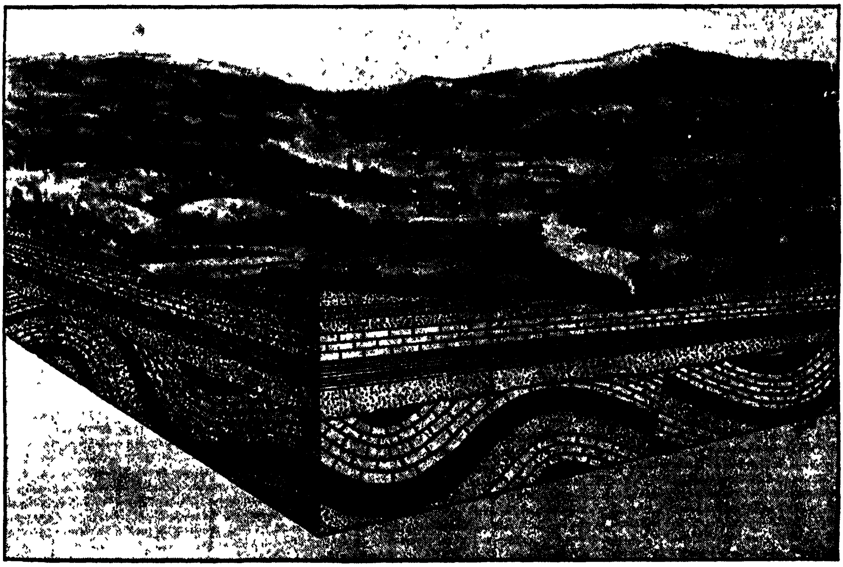

Fig. 146. Angular unconformity between older folded rocks and flat-lying younger rocks. Between time of deposition of older and younger series of beds the older rocks were folded and faulted, uplifted above sea level and truncated by erosion. Later they were submerged beneath the sea again and overlain with younger sediments. *By John Jesse Hayes.*

these quakes are strong enough to be felt locally. Fortunately, the proportion of destructive earthquakes is very small. For one reason, many quakes occur in sparsely settled regions or out beneath the sea floor, so that even though they may be violent in intensity they may not be destructive to life and property. However, by far the greatest number of earthquakes are so mild that little or no damage is done even when they occur in regions of dense population.

Causes of earthquakes. Volcanic eruptions are often preceded and invariably accompanied by earth tremors, but these are very local in character. Most of the great quakes have been caused by faulting in the rocks in the earth's crust. Where these fault planes reach the surface, roads, fences, and tracks may be offset several feet, or one side lifted up with respect to the other. Some fault lines have been traced for many miles after an earthquake by these jogs and scarps. The displacement effects of vertical faulting in the rocks beneath the ocean are not readily observable, but the movement may create huge waves which are capable of causing considerable damage on shore. A great sea wave produced by an earthquake near the Aleutian Islands in Alaska in 1946 rolled equator-

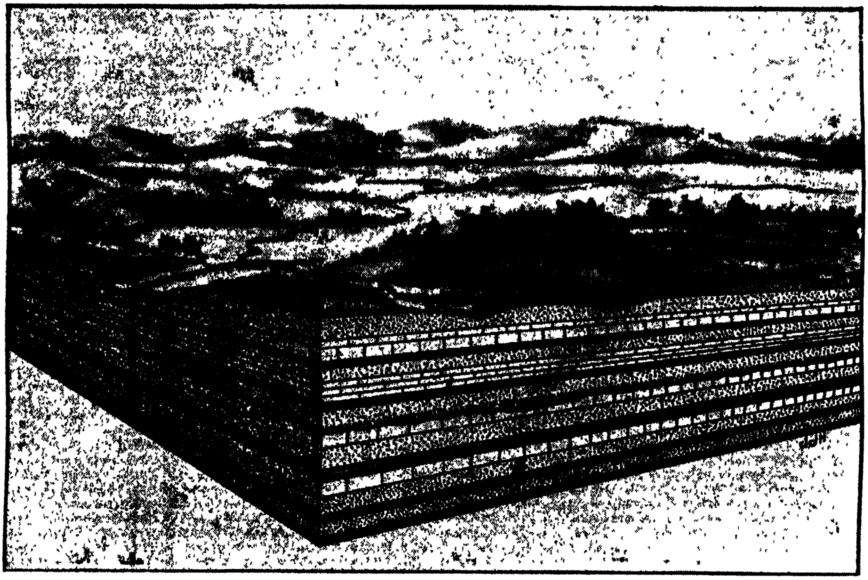

Fig. 147. Erosional unconformity. Following deposition of older sediments the region was lifted above sea level and the surficial rocks were unevenly eroded but were not folded or faulted. Subsequently a second submergence permitted the deposition of the structurally conformable younger sediments. ***By John Jesse Hayes.***

ward through the Pacific causing much damage in the island archipelagos en route.

The disturbance caused by faulting is naturally greatest in the immediate vicinity of the fault plane, but the shock may be transmitted through the rocks for great distances (Figs. 148 and 149).

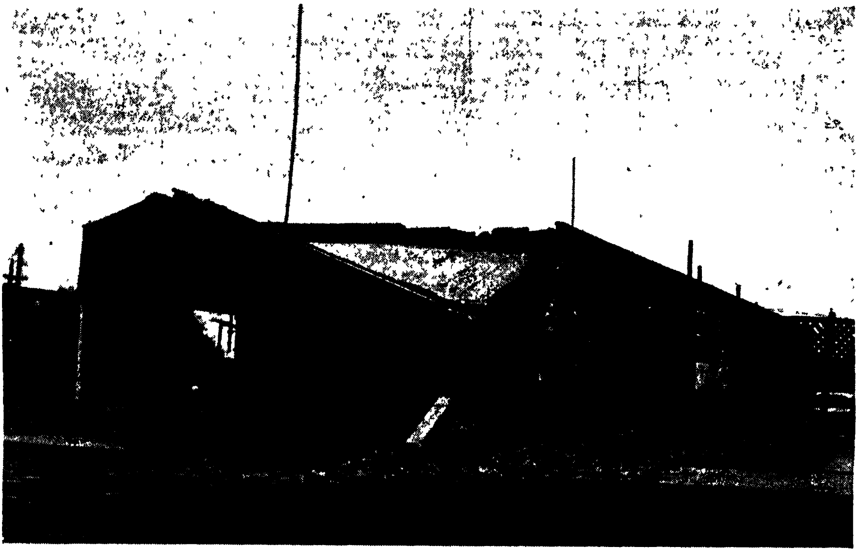

Fig. 148. The collapse of this brick arcade was caused by earthquake shock. Brawley, California, May 20, 1940. *Courtesy Norman E. A. Hinds and the University of California.*

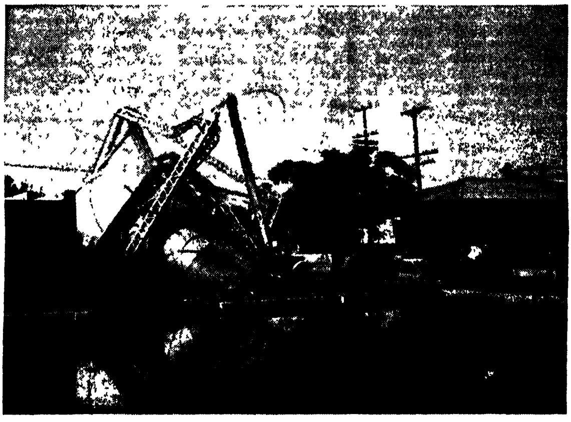

Fig. 149. The municipal water tank at Holtville, California, couldn't take it when the earth quaked. ***By J. P. Buwalda, June,*** **1940.** ***Courtesy Norman E. A. Hinds and the University of California.***

Earthquake belts. Most of the active faults (and active volcanoes) occur in belts of crustal instability. One seismic (earthquake) belt borders the Pacific, including the western coast of the two Americas, the Aleutian Islands, the eastern coast of Asia (especially the Island groups) and Antarctica. Another belt borders the Mediterranean and extends eastward through the mountain chains of southern Asia. The islands of the Caribbean lie in a shorter but nevertheless active belt of seismic disturbance.

Descriptions of earthquakes. A very vivid description of what happens when a violent earthquake occurs has been recorded in a book by the late Major C. E. Dutton, from which the following is quoted:

> When the great earthquake comes, it comes quickly and is quickly gone. Its duration is generally a matter of seconds rather than of minutes, though instances have been in which it lasted from three to four minutes. Perhaps forty-five seconds would be a fair average. The first sensation is a confused murmuring sound of a strange and even weird character. Almost simultaneously loose objects begin to tremble and chatter. Sometimes, almost in an instant, sometimes more gradually, but always quickly, the sound becomes a roar, the chattering becomes a crashing. The rapid quiver grows into a rude, violent shaking of increasing amplitude. Everything beneath seems beaten with rapid blows of measureless power. Loose objects begin to fly about; those that are lightly hung break from their fastenings. The shaking increases in violence. The floor begins to heave and rock like a boat on the waves. The plastering falls, the walls crack, the chimneys go crashing down, everything moves, heaves, tosses. Huge waves seem to rush under the foundations with the swiftness of a gale. The swing now becomes longer and still more powerful. The walls crack open. A sudden lurch throws out the front wall into the street, or tears off or shakes down in rubble the whole corner of the building. Then comes a longer swaying motion, not like a ship at sea, but more rapid; not alone from side to side, but forward and backward as well, and both motions combined into a wriggle which it seems impossible for anything to withstand. It is this compound, figure-8 motion which is so destructive, rending asunder the strongest structures as if they were adobe. It is the culmination of the quake. It settles into a more regular swing of decreasing amplitude, then suddenly abates and the motions cease.
>
> Or suppose we are out in the country and the earthquake comes suddenly upon us. The first sensation is the sound. It is wholly unlike anything we have ever heard before unless we have already had a similar experience. It is a strange murmur. Some liken it to the sighing of pine trees in the wind, or to falling rain; others to

> the distant roar of the surf, others to the far-off rumble of the railway train; others to distant thunder. It grows louder. The earth begins to quiver, then to shake rudely. Soon the ground begins to heave. Then it is actually seen to be traversed by visible waves somewhat like waves at sea, but of less height and moving much more swiftly. The sound becomes a roar. It is difficult to stand, and at length it becomes impossible to do so. The victim flings himself to the ground to avoid being dashed to it, or he clings to a convenient sapling, or fence-post, to avoid being overthrown. The trees are seen to sway sometimes through large arcs, and are said, doubtless with exaggeration, to touch the ground with their branches, first on one side, then on the other. As the waves rush past, the ground on the crests opens in cracks which close again in the troughs. As they close, the squeezed-out air blows out sand and gravel, and sometimes sand and water are spurted high in air. The roar becomes appalling. Through its din are heard loud, deep, solemn booms that seem like the voice of the Eternal One, speaking out of the depths of the universe. Suddenly this storm subsides, the earth comes speedily to rest and all is over.
>
> And yet this feeble description suggests but a single instance, or a few instances having a general similarity. There are many variations of detail in the incidents of great earthquakes. In some the full vigour of the shock comes . . . with an almost explosive suddenness. People find themselves suddenly thrown to the earth, the ground literally knocked from under their feet. Sometimes the rolling waves of soil are absent and the motion is a rude quiver, rapidly vibrating in every direction, twisting, contorting, wrenching the ground, as if in a determined effort to shake it into dust. Sometimes the most pronounced motion is vertical, as if the earth beneath were being hammered upward by a quick repetition of strokes.[1]

A number of extremely destructive earthquakes have occurred in comparatively recent times. Falling buildings, disastrous fires which are difficult to conquer because the earth movements tear asunder the water pipes, and enormous sea-waves may exact an appalling life and property toll. Over 140,000 people were killed or missing after the Japanese quake of 1923. Estimates of the property damage range from 2½ to 3 billion dollars. The main shock came at noon on September first. During the afternoon "there were five shocks all of destructive or semi-destructive strength, and on the following day three. By the end of the month no fewer than 1,256 shocks were recorded at Tokyo, of which more than half were strong enough to be felt." [2]

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[1] Dutton, C. E. *Earthquakes*, pp. 12-16. New York: G. P. Putnam's Sons, 1904.

[2] Davison, Charles. *The Japanese Earthquake of 1923*, p. 5. London: Thomas Murphy & Co., 1931.

The epicentre, or central point, of the Japanese earthquake was south of Tokyo and Yokohama in Sagami Bay. The most violent earth movements took place beneath the waters of the bay; the sea floor sank 1,312 feet at one point and rose 755 feet less than three miles away. Most of the surrounding shoreline was permanently elevated to a maximum height of six and one-half feet. Here occurred the greatest damage; 95 per cent of the houses in some of the towns lying along the north shore of Sagami Bay collapsed.

> About three miles to the north of Atami, the prefecture of Kanagawa begins, and with it, the area of great destruction. Close to the boundary line is the small town of Manazuru, that contained 1,258 houses before the earthquake. Of these, 20.9 per cent collapsed, the total loss being brought up by fire to 90.0 per cent. Manazuru Point, the end of an old lava stream from Mount Hakone, runs out about 2½ miles into the sea. Here, the sea retreated almost immediately after the earthquake. While the land was thus laid bare, water spurted up with each shock from numerous places to a height of several feet. In a few minutes, the sea returned. There was no wave. The water simply rose very rapidly, but it came in with such force that large boulders and pine trees were tossed about "like peas and straws in a boiling pot."
>
> The top of the peninsula was so shaken up that persons walking across it sank up to their knees in soft earth. Potatoes were thrown out of the ground as completely as if they had been dug by hand. Large pine and camphor trees were in places buried leaving only the tips of the branches above ground. The wells in this district are lined with earthen tile pipes about 18 inches in diameter, and many of these pipes were forced out of the ground and were left standing up like chimneys, some of them about 10 feet high.
>
> During the rest of September 1 and all of September 2, aftershocks occurred so frequently in this district as to be almost continuous. At intervals of about ten minutes, came more severe shocks, strong enough to throw down people who were walking. The shocks seemed to come directly from underneath and were extremely painful to those standing on rock or hard ground.
>
> A short distance to the south of Odawara lay the villages of Kataura and Nebukawa. A hamlet belonging to the former and containing more than sixty families was completely buried under a mass of rock and sand about one hundred feet in thickness, that fell from the neighbouring mountain. Close by, the river Nebukawa flows down, a mountain stream that, mixing with the earth brought down by landslips, had formed a mud-flow about 200 yards wide and perhaps 50 feet in depth. The village of Nebukawa at its mouth was swept by it into the sea. At the moment of the earthquake, a train for Manazuru had arrived at Nebukawa station with more than 200

> passengers. Both station and train were carried away by the torrents and mud-flow to the bottom of Sagami Bay, and not one soul in either escaped.
>
> Of the old town of Odawara, hardly a trace remained. With the violent vertical shocks, landslips occurred at many places, bridges collapsed, and numerous giant trees were uprooted or snapped in two. In the town and neighbourhood, more than 5,500 houses were thrown down. The fires, that started in 12 different places, soon under the furious gale combined into one great mass of flame that covered the whole town and burned more than 2,300 houses in the central part. Of 4,835 houses that existed on the morning of September 1, only about 264, or 6.7 per cent, remained.[3]

The havoc created by this earthquake was by no means confined to the vicinity of Sagami Bay; destruction of property was spread over seven prefectures (provinces). The greatest loss of life (83 per cent of the total deaths) occurred in densely populated Tokyo and Yokohama, where fires, started by the earthquake and fanned by winds of gale velocity, devastated the greater part of those two cities. An estimated 40,000 people had gathered in an open space near the center of Tokyo when a sudden shift of the wind carried the fire across their place of refuge; not a single individual survived this holocaust.

Great as the loss of life was in the Japanese quake of 1923, it has been exceeded several times in the past. Up to 180,000 people were killed, mainly by landslides, (Chapter 7), in the Kansu and Shenshi provinces of China in 1920. Destructive earthquakes have visited the Sagami Bay district of Japan before; one of these, in 1703, caused the death of 200,000 people. Thirty-four years later, 300,000 were killed in India by a violent quake. The highest loss of life on record is an estimated death toll of 830,000 in an earthquake occurring in Shenshi province, China, in 1556. It is surprising that the earth cracks which open and close during quakes have not engulfed more people than they have. During Japan's long earthquake history there is only one authenticated case of this sort. In the severe quake which virtually destroyed the city of Fukui in July, 1948, a woman was buried up to her neck in a crack that opened in her rice paddy. Before neighbors attracted by her screams could rescue her, the crack contracted and crushed her to death.

Seismology. Earthquakes set up vibrations or waves which go to all parts of the earth. The study of earthquakes and earthquake waves is known as *seismology.*

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[3] Davison, Charles, *op. cit.*, pp. 34-35.

There are three sets of earthquake waves: two, the *primary* and *secondary* waves, pass through the earth; the third set, the *long* waves, passes around the earth. The primary and secondary waves are separate types of waves which vibrate in different directions and travel at different speeds. The earth acts as a rigid solid in transmitting these waves. Instruments have been invented which record on a revolving drum the primary, secondary, and long waves as they reach the point at which the instrument is located. These instruments are known as *seismographs,* and the zig-zag line that is drawn on the drum when an earthquake is recorded is a *seismogram.* Information as to the location of an earthquake, the time at which it occurred, and its intensity can be compiled from seismograms obtained at a number of separate stations. Seismographs pick up earth tremors which would otherwise be unnoticed because the faulting occurred in uninhabited areas or beneath the sea.

It is as yet impossible to forecast when an earthquake will take place. Most of the active faults have been mapped, so that we know in a general way what areas are liable to be visited by quakes in the future. In such areas it is wise so to build that earthquake damage will be at a minimum. Deep alluvium and filled-in ground should be avoided, as these have a tendency to magnify the shocks occurring in the underlying bed rock. The San Francisco earthquake of 1906 caused much greater damage to the buildings on the alluvial plain than to those on the adjacent bed-rock hills. Buildings should be constructed of such material that they will sway without breaking. Stone and brick structures are inferior to wooden buildings in this regard, but wooden buildings are an easy prey to the fires that follow. Reinforced concrete is the best building material. Buildings of this type in downtown Tokyo were left standing among completely razed structures of other types in the earthquake of 1923.

Seismology has been used by the petroleum geologist in searching for buried structures favorable to the accumulation of oil and gas. Explosives are set off, creating miniature earthquakes which send waves downward through the rocks. Where a rock stratum or mass of different elasticity is encountered, some of the waves are reflected back to the surface and are caught by seismographs set up at different points. From the seismograms thus obtained, it is possible to determine the structure of the buried rocks. This procedure is described in more detail in Chapter 17.

MOUNTAINS

A mountain is a lofty elevation of rock; it need not be of great height above sea-level, but it must rise conspicuously above nearby land surfaces. The distinction between a hill and a mountain is a matter more of location than of height. In regions of low or moderate relief the "mountains," according to local nomenclature, may be lower than some of the "hills" in more rugged areas. As a general rule, the highest points in a region, whether they reach elevations of 500 or 5,000 or more feet above the surrounding lowlands, are called mountains; the much lesser heights are referred to as hills. Mountains may be isolated peaks, elongate ridges, or a group of summits capping a relatively high area.

The highest mountains in low latitudes, and all mountains in high latitudes, rise above the level of perpetual snow. But whether snow-clad the year round or not, mountains attract thousands of people annually. Many are lured by more comfortable summer temperatures and magnificent vistas, while others seek the recreational features such as mountain climbing, fishing, hunting, and winter sports.

Valuable forests may occupy the flanks of mountains. The winter snows store water which is tapped by the heads of rivers. Some great cities have built long pipe lines into mountainous areas in order to obtain a consistent year-round flow of uncontaminated and soft water. Mountain chains exert a strong effect on climate; the winds in crossing a range of mountains are pushed upward to the point where lower temperatures force the precipitation of their contained moisture on the windward side. After crossing the mountains the winds descend and the air is warmed by compression (*adiabatic heating*). This increases the air's capacity to hold moisture. For these reasons dryness results on the leeward side.

Origin of mountains. The elevation of mountains is due, directly or indirectly, to diastrophism. The diastrophism may be of three types: deepseated movements, horizontal movements, or vertical movements. Movements deep within the earth's crust permit the escape of lava to the surface. If this lava flows (or is blown) through a circular vent, a volcanic cone is formed which in time may rise high enough to be a mountain. Lateral compression of the earth's crust creates horizontal movements, which produce folded rocks and overthrust faults. Tension in the crust produces normal faults. Folded and faulted mountains are due initially to horizontal movements. Vertical upward movements of the earth's crust, or *uplifts,* provided the elevation needed for most of our present-day mountain ranges. Uplifts may occur, and in many cases have occurred, in regions which have previously suffered intense diastrophism of the compressional type. Furthermore, uplifts may be recurrent so that mountain systems are periodically *rejuvenated.*

After *diastrophism* has produced the *elevation* necessary for mountains, *erosion* carves the mountain *topography.* Volcanoes are an exception, however, to both of these rules. Diastrophism merely permits the escape of lava; the mountain is built by volcanic activity. Erosion, therefore, plays no part in forming a volcanic mountain, although it may modify its shape, and eventually will destroy it altogether (as it will other mountains). With this exception, erosion is as essential to the formation of mountains as is diastrophism. The increased elevation brought on by folding, faulting, simple uplift, or a combination of these, creates increased stream gradients, and erosion by running water is accelerated. Deep valleys are carved; headward erosion of many valleys back into the divides creates mountains. Ice and other agents of erosion may assist in this sculpturing. In other words *all mountains except volcanoes are residual features, representing a stage between the elevation of a great mass of rock by diastrophism and its destruction by erosion.*

The base-leveling of an uplifted area may be complicated by its continued rising, through isostasy, to compensate for the weight of the sediment removed by erosion. One must postulate a lag in the isostatic adjustment between the areas of erosion (unloading) and deposition (loading) in order to explain base leveling at all.

Volcanoes. Volcanoes (described in Chapter 10) are unique among mountains because they are built up by the accretion of lava and ejectmenta instead of being sculptured out of preexisting rock. They may be unique also in standing some distance from other mountains and in exhibiting unusual perfection of symmetry. For these reasons some volcanoes, such as Rainier, Shasta, Popocatopetl, Etna, and Fujiyama, are among our best known and most beautiful mountains.

The shapes of some volcanic peaks have been considerably modified by mountain glaciers. In addition, volcanoes are eroded by other agents, mainly running water. Cinder cones are especially susceptible. Therefore, a volcano will exist as a mountain for only a brief period as geologic time is measured; our volcanic peaks of today were built a relatively short time ago. In fact, some have been active during human history. Once erosion has completely destroyed a volcanic mountain there remains the neck or conduit through which the lava poured upward from deeper in the crust. In many cases the rock in this neck is harder than the surrounding rock so will become a prominent topographic feature during the lowering of the local surface by erosion. Some mountains, such as the Spanish Peaks in Colorado, are formed in this way. Most volcanic necks are smaller. They may be referred to locally as buttes, although geologists tend to restrict this term to features of somewhat similar topography, but which are composed of flat-lying layered rock. Dikes, inclined sills, and uncovered laccoliths may likewise resist erosion to such an extent that ridges, hills, and even mountains result. All of these features except the volcanic cones themselves are carved by differential erosion, and therefore differ but little in origin from the mountains described in subsequent paragraphs.

Folded-rock mountains. Some mountain chains, such as the Appalachians, consist of sedimentary rocks that have been folded into a series of waves like pleats in a skirt. The sediments were originally deposited in a great geosyncline, the floor of which sank as the material was deposited. In this way thousands of feet of sediment was deposited before diastrophism raised the geosynclinal trough to such heights that the sea could no longer enter. A sinking geosyncline can be described as a wedge forcing its way into the earth's crust. This wedge contains rock that is weaker than the rock on either side; it eventually succumbs to the compressive forces in the crust by forming a series of folds and, perhaps, overthrust faults. This diastrophism may be aided by the expansive forces set up by the higher temperatures encountered with deeper burial.

Diagrammatic reproduction of the folds exposed in mountain chains places the apices of some of the anticlines thousands of feet above the summits of the present mountains. It has been concluded by some geologists that the mountains themselves at one time reached these enormous heights, but it is more likely that folding was sufficiently slow so that the agents of erosion truncated the tops of the anticlines as they rose. In no mountain range of today, at any rate, does the topography ever approximately conform to the rock structure, in that the ridges are anticlines and the valleys synclines. Once erosion has truncated the top of an anticline it proceeds differentially, the resistant rock layers on the flanks of anticlines (and synclines) making hogback ridges, and the softer layers eroding into valleys. This is the typical topography of folded rock mountains.

The traceable history of the earth is divided into a number of periods; each period represents many millions of years. It takes the forces of erosion less than the span of an average period to destroy a mountain range. But erosion does not destroy the folded rock structure, so if diastrophism re-elevates a region of folded rocks, differential down-cutting will re-create hogback ridges with intervening valleys. Most of our folded rock ranges of today are *rejuvenated* mountains; in some instances they have been planed down by erosion and rejuvenated several times in the geologic past. Such mountains have two or more birthdays, the first the time of the original folding and the last the time of the most recent uplift. The Appalachian Range was originally folded during a far distant geologic period. Before the close of the next period, still several hundreds of million of years ago, the entire region was peneplained. Subsequently these mountains have been uplifted, carved out by erosion, and destroyed, or partly destroyed, several times. The Appalachians and all of the other mountains now existing in the world were last uplifted during a fairly recent period. Mountains elevated earlier have been destroyed, just as the present mountains will be destroyed in a short space of geologic time unless further uplifts occur.

Many mountain chains, including those with the highest peaks, consists of more than folded sedimentary rocks. They also contain great masses of granite and other igneous rocks, and various kinds of metamorphic rock. These rocks are very resistant to erosion, so that when they are uplifted they are soon isolated as peaks by the removal of surrounding, less resistant rocks. Crystalline (igneous and metamorphic) rocks occur in mountain chains in two quite different structural relationships. In one, an arching of the crust elevates the hard rock floor on which the sedimentary rocks were deposited to such heights that the floor is uncovered by erosion of the sedimentary rock veneer across the top of the arch. Because of the hardness of this rock it will erode more slowly than the sedimentary rocks on the flanks. In time the igneous or metamorphic rock in the core will be sculptured into sharp peaks and narrow valleys. The jagged sedimentary rocks on the flanks, because they consist of tilted layered rocks of varying hardness, will be eroded into relatively low hogbacks with intervening valleys which parallel the crystalline rock range. The Front Range of the Rocky Mountains illustrates this type of mountain system. The peaks are carved from granite; parallel to and in front of them to the east are hogbacks of tilted sedimentary rocks. The hard igneous or metamorphic rocks forming the core of mountain ranges falling into this classification are *older* than the associated sedimentary rocks; the crystalline rocks were at one time the floor on which the sedimentary rocks were deposited, as shown by the depositional contact between the two.

The other type of "hard rock" mountain range has a core of igneous rock which is *younger* than the associated sediments. In this case great batholiths and other bodies of magma were intruded into the sedimentary rock formations as they were being folded; the contact is an uneven one because the magma pushed and "burned" its way into the sediments. When diastrophism lifts a rock complex of this character high above sea-level the agents of erosion strip off the roof of sedimentary rock and expose the intruded igneous rock. Subsequently erosion proceeds differentially; the softer sedimentary rock is stripped down to low elevations while the relatively resistant igneous rock is carved into a rugged mountain system. The main ranges of the Rockies, the Sierra Nevadas, Cascades, and many other mountain chains are of this type.

But not even the mountains made of igneous and metamorphic rock are everlasting. They, too, are peneplained in time by erosion. Likewise they can be (and have been) rejuvenated by uplift. The hard cores are not destroyed when the mountains are planed down; the renewed erosion brought about by an uplift will re-create mountains out of the harder rocks by removing at a faster rate the associated less resistant rocks.

Faulted mountains. Some mountain ranges have been elevated by faulting. Erosion carves mountains out of the upraised rock, at the same time obliterating the fault scarp. Fault mountains of this type will be destroyed when erosion lowers the surface of the upfaulted rock to the level of the surface across the fault. However, if faulting has thrown together rocks of unequal hardness, differential erosion will take place whenever the rock surfaces adjacent to the fault stand above base level. Mountains can therefore be made by the uplift of an area in which the rocks were faulted during a past period of diastrophism. The ideal condition for this type of mountain range is where crystalline rocks have been faulted against relatively soft sedimentary rocks. Some of the ranges of the Rocky Mountain system have had this origin (Fig. 150).

There are, therefore, two types of faulted mountains: one in which the mountains are carved from an upfaulted block of rock, and the other in which differential erosion has created mountains out of uplifted rocks which were faulted during a previous period of diastrophism.

The best known example of fault block mountains are the Great Basin ranges which lie between the Rockies and the Sierra Nevadas. These ranges have been carved from great blocks of rock which were faulted up and simultaneously tilted.

Mountains of the butte and mesa type. There remain to be described the mountains which are formed during the destruc-

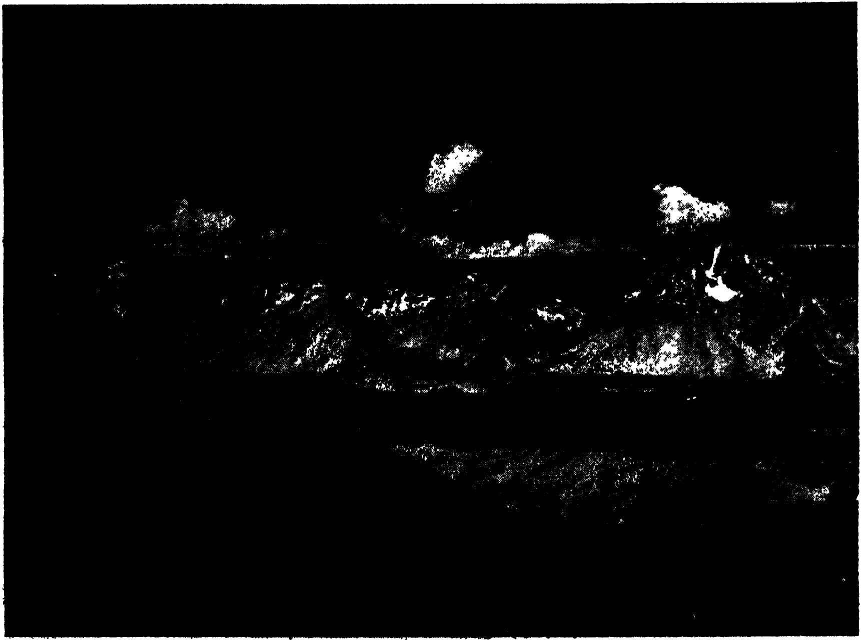

Fig. 150. Upfaulted resistant crystalline rocks in background; relatively soft sedimentary rocks in low area in fore-and middleground. Teton Mountains and Jackson Lake, Wyoming. *Courtesy Union Pacific Railroad.*

tion of an uplifted region, such as a plateau, which is underlain by flat lying rocks. Because the latter tend to be worn down more evenly than do the mountains consisting of folded or crystalline rocks, they have lesser magnitude as a general rule. They are formed because some of the flat-lying beds are more resistant to the forces of erosion than others; these become the "cap rocks" of mesas and buttes, topographic features which were described in Chapter 5. When erosion has completely removed a cap rock, the underlying softer rocks are soon stripped off, and the next hard layer becomes the cap. The harder layers on the flanks of a butte or mesa, the cap rocks of the future, can be recognized by their steep faces which interrupt the normal slope of the hillside. Also, the softer rock immediately above a resistant bed may be cut back, creating a bench or terrace.

Most mesas and buttes are capped by hard beds of sandstone. Other relatively resistant rocks are limestones and solidified lavas. The softer rock that lies between the hard formations is, in most instances, a shale. Lava-capped mesas of sufficient height to qualify as mountains occur in southern Colorado, New Mexico, and elsewhere. The Southwest also contains many mesas and buttes with sandstone cap rocks. Erosion by tributaries of the Colorado River in Grand Canyon has formed buttes high enough to be considered mountains.

METAMORPHISM AND METAMORPHIC ROCKS

Metamorphism literally means change of form. Igneous and sedimentary rocks in the earth's crust may be changed (metamorphosed) into quite dissimilar rocks, called metamorphic rocks. These rocks have either a characteristic texture or mineral assemblage, or both, which distinguish them from all other rock types.

Diastrophism is a primary cause of metamorphism. In some cases it operates directly, as when compressive movements in the earth's crust create greater pressures than the original rocks can stand, with the result that these rocks become metamorphosed. This is known as *dynamic metamorphism.* Metamorphism by vertical pressure and heat may be brought about by deep burial, in which case diastrophism is a less direct but none the less essential cause of metamorphism, for deep burial can occur only through crustal movements which depress a part of the crust so that deposition of sediment may take place. Metamorphism caused by the weight of overlying rock, plus increased earth temperature due to greater depths, is called *static metamorphism.*

Metamorphism can also result from the intrusion of magma. This process, known as *contact metamorphism,* was described in the preceding chapter. The results of contact metamorphism differ considerably from those of *regional metamorphism,* which includes both dynamic and static metamorphism. Contact metamorphism, as the name implies, is confined to a relatively narrow zone adjacent to the contact of an igneous intrusive, whereas regional metamorphism affects a vastly greater volume of rock. Magmas may also introduce new elements and compounds into the adjacent rocks, so that new minerals, which consist, in part at least, of elements which were not hitherto present, are formed in the contact rock. In regional metamorphism also, new minerals may be made, but these are formed solely through the rearrangement of elements already present. Chemical analyses of a rock before and after regional metamorphism would be very similar.

Agents of metamorphism. The agents of metamorphism are heat, pressure, water, and gases. As a general rule these agents are all in operation during metamorphism, so the product is a result of a combination of forces. However, in different types of metamorphism some agents may be decidedly more active than others.

Relatively high temperatures may be due solely to deep burial. Temperature increases below the surface so that a rock buried a few thousands of feet deep is heated to an appreciably higher temperature than a rock lying at or near the surface. Heat is also generated by friction during diastrophism if the forces are great enough to cause faulting, shearing, or rock flowage. Another source of heat is intruded magma, of far greater importance in contact than in regional metamorphism. The main function of heat in metamorphism is to dehydrate the water-containing minerals and to speed up the chemical and physical processes that take place. The solubility of minerals in the interstitial (between the grains) water is greatly increased by heat, and very high temperatures soften the mineral grains and allow them to change their shapes under pressure.

Abnormal pressures on the rocks in the earth's crust may be created in several ways, Pressure can be caused by deep burial, for the weight of a few thousands of feet of overlying rock is very great. Some magmas are intruded with sufficient force to disrupt and push aside the rocks in their way. But probably the most intense pressures are those created by diastrophism of the mountain-building type. In this case the rocks may be greatly squeezed by pressures which vary widely in intensity in different directions. The result may be a profound change in the character of the rock. High pressures also aid the solution of minerals in interstitial water. Where pressures are much greater in one direction than another, the minerals surviving the metamorphism may suffer change in shape, and the new minerals which form will have orientations controlled by the pressure directions. The effects of pressure will be more fully described in the following section where the results of metamorphism are discussed.

Water is essential to metamorphism. It may be present as connate water, which occurs between the grains in a sedimentary rock and which is residual from the water in which the sediments were deposited. It may be meteoric (rain) water which has joined the ground-water circulation; or the water may be of magmatic origin, either left in an igneous rock at the time it crystallized or occurring in any type of rock by penetration from an igneous intrusion somewhere in the vicinity. During metamorphism additional water may be made available through the dehydration of water-containing minerals in the rock. The main function of water during metamorphism is to act as a solvent for compounds in the rock which are unstable under the changed conditions of temperature and pressure. The material thus taken into solution in the interstitial water immediately reprecipitates in forms which are stable in the new environment. Water, therefore, acts mainly as a vehicle of metamorphism.

Other agents of metamorphism are compounds and gases in solution in the interstitial water, and similar materials which are released from the minerals in the rock during metamorphism. Connate water contains salt and other compounds which were in solution in the original sea water. Meteoric water may contain oxygen, carbon dioxide, and various soluble solids picked up during its travels. The elements and compounds, both solid and gaseous, which may be in solution in magmatic water are many and varied. Metamorphism of rocks containing carbonate minerals, such as limestones and dolomites, may release carbon dioxide; pyrite and other sulphide minerals are sources of sulphur. These various elements and compounds are available for chemical interactions with the minerals composing the rocks undergoing metamorphism. If the temperatures are high enough, these *volatile* fractions of the rock, including the interstitial water, may be in gaseous form, but the reactions taking place are the same.

Results of metamorphism. The principal result of metamorphism is the formation of metamorphic rocks from rocks that were originally sedimentary or igneous. This result may be obtained through a simple process, such as the re-crystallization of calcite, which converts limestone to marble, but in most cases it is brought about by several processes operating at the same time.

One result of metamorphism is the *dehydration* of minerals that formerly contained water. Thus the clay minerals, which are hydrous silicates of aluminum, may be changed to anhydrous aluminous silicates through the expulsion of the water of crystallization (chemically combined water). A somewhat analogous process is *devolatilization,* best illustrated by coal, which is altered from lignite through bituminous to anthracite and even graphite (pure carbon) by metamorphic processes which cause the volatile constituents to be driven out of the carbonaceous material.

Recrystallization of the minerals contained in the rocks is a very common result of metamorphism. It occurs when increased temperatures or pressures, or both, create an environment in which the original minerals can no longer exist. Consequently they recrystallize into forms which are stable in this new environment. In its simplest form recrystallization recreates the same mineral, but in larger, interlocking grains. Marble is an example. The smaller grains of calcite in a limestone become unstable at high temperatures and pressures and go into solution in the interstitial water, to be immediately reprecipitated on the larger grains. The condition of instability is corrected by the development of large crystals, which grow at the expense of the smaller crystals. More often the elements composing some of the minerals in a rock undergoing metamorphism are forced to recombine into an entirely new set of minerals which are stable under the changed conditions. Some of these metamorphic minerals, such as mica and garnet, may be formed also by other processes, but certain other minerals are characteristic of metamorphism and are found only in rocks of this type. Examples of the latter are three silicates of aluminum: sillimanite, kyanite, and andalusite.

Where the pressures to which rocks undergoing metamorphism are subjected are much greater in one direction than another, profound changes are made in the physical appearance of the rock. Minerals, such as quartz and feldspar, which remain chemically stable through the metamorphic action, may be crushed or squeezed, so that the grains become elongated normal to the direction of most intense pressure. New minerals formed through recrystallization, if they tend to be tabular (such as mica) or elongate (such as hornblende), naturally grow most in the direction of least resistance, which is at right angles to the direction of most intense pressure. Because this direction of greatest force is the same at any one place, the minerals deformed by squeezing, and the tabular and elongate crystals produced during recrystallization, will all have parallel orientation of their longer axes. The result is a *banding* or *foliation* (segregation of the minerals into dominant planes) of the rock. Fine-grained metamorphic rocks, such as slate, may have a well developed *cleavage*. The cleavage planes likewise lie normal to the direction of most intense pressures. The metamorphism of a sedimentary rock may or may not destroy all traces of the original bedding planes; if the latter are still visible they show no parallelism (except through mere coincidence) with any banding or cleavage planes that may be present.

Hot, deeply buried rocks subjected to strong pressures may become folded, crumpled, and otherwise deformed through *flowage*. Any pre-existing bands, including veins and dikes of igneous rock.

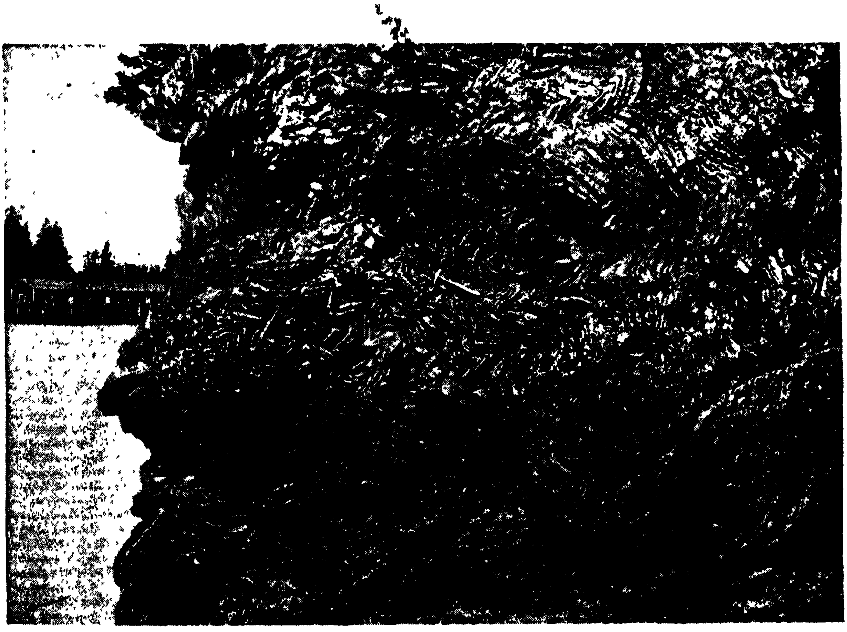

Fig. 151. Contorted chert beds, Seldovic Bay, Alaska. *By U. S. Grant. Courtesy Geological Survey, U. S. Department of the Interior.*

are contorted by this process. Crumpled, banded rocks are fairly characteristic of the older metamorphic rocks of the earth's crust (Figs. 151 and 152).

Varieties of metamorphic rocks. Metamorphic rocks have various characteristics that distinguish them from other types of rocks and from each other. In many metamorphic rocks *texture* is a distinguishing medium. As noted in a preceding paragraph, the minerals may occur in distinct bands. If these bands are fine the texture is spoken of as *schistose;* if coarse, the texture is *gneissic.* Sufficient characteristics of the original rock remain in some metamorphic rocks to permit recognition, in which case the name of the original rock is coupled to that of the metamorphic rock (example: *granite-gneiss*). In other cases metamorphism has obliterated the identity of

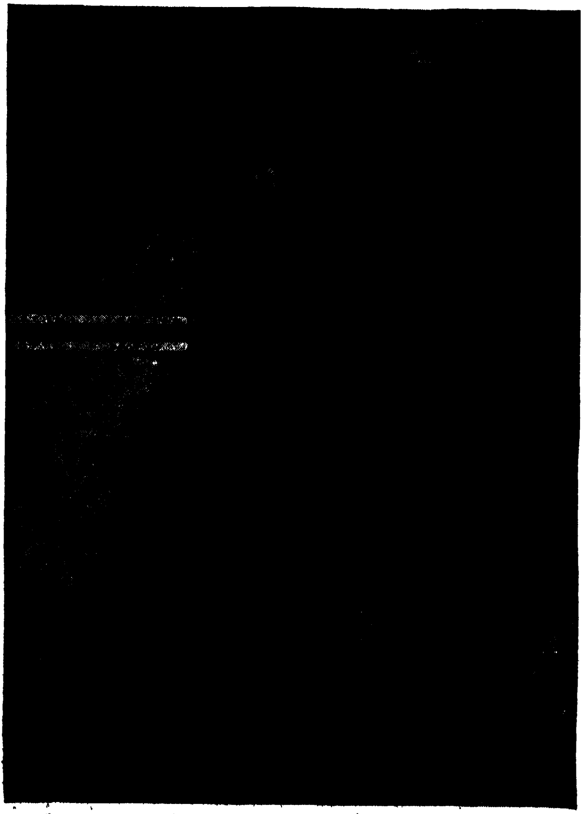

Fig. 152. Highly contorted schist injected by gold-bearing quartz veins. Scale is six inches in length. On 2600-foot level of Homestake Mine, Lead, South Dakota. *Courtesy Homestake Mining Company.*

the original rock. However, the texture of a rock has a decided control on grain size after metamorphism; dense rocks such as basalts and shales as a general rule produce finer-grained metamorphic rocks than do the relatively coarse-grained granites and sandstones. The mineral content of a few metamorphic rocks, such as marble and serpentine, determine its identity, in other cases the presence of a mineral creates a sub-variety (examples: *mica schist*). A table of the more common metamorphic rocks, classified according to the original rock, follows:

METAMORPHIC ROCK TABLE

Original Rock	*Metamorphic Rock*
I IGNEOUS	
Granular rock	Gneiss
Dense rock	Schist
II. SEDIMENTARY	
Limestone	Marble
Sandstone	Quartzite
Sandstone, quartzite, conglomerate	Gneiss
Shale	Slate Schist
"Soft" (lignite or bituminous) coal	"Hard" (anthracite) coal or graphite

Gneisses are hard, coarsely banded rocks (Fig. 153). The original rock was a coarse-grained igneous or sedimentary rock. Most gneisses are derived from granite and consist largely of feldspar and quartz. Mica is usually present, with the plates parallel to the banding. Many gneisses are severely crumpled, due to a change in the direction of pressure after the bands are formed.

A schist is a finely banded, foliated rock that tends to split parallel to the bands. Schists are derived from dense igneous or sedimentary rock. Mica is especially common in thin books and plates parallel to the banding. Flaky particles of talc, chlorite, or graphite may be present, oriented in the same manner. In some schists coarse minerals, created by the metamorphism, occur as "knots" or *metacrysts* around which the layers bend. Garnet, magnetite, pyrite, and several less common minerals, which are found in metamorphic rocks only, may appear as metacrysts.

Quartzite is both a sedimentary and a metamorphic rock. Sedimentary quartzites (Chapter 9) are merely silica-cemented sandstones; metamorphic quartzites are produced by the recrystallization of the quartz grains into an interlocking aggregate.

Serpentine is formed through the chemical alteration of iron and magnesium containing minerals which occur in dark-colored igneous rocks. It is green in color and a relatively soft rock.

Recrystallization of limestone produces *marble.* The dominant mineral constituent of both limestone and marble is calcite, but in marble the calcite crystals are coarser and are interlocking. For this reason the rock takes a good polish. Some marbles are banded and beautifully colored.

Slate is formed by the metamorphism of shale. It has a well developed cleavage which makes the rock of considerable value for roofing and other purposes. Most slates are black, but shades of red and green also occur.

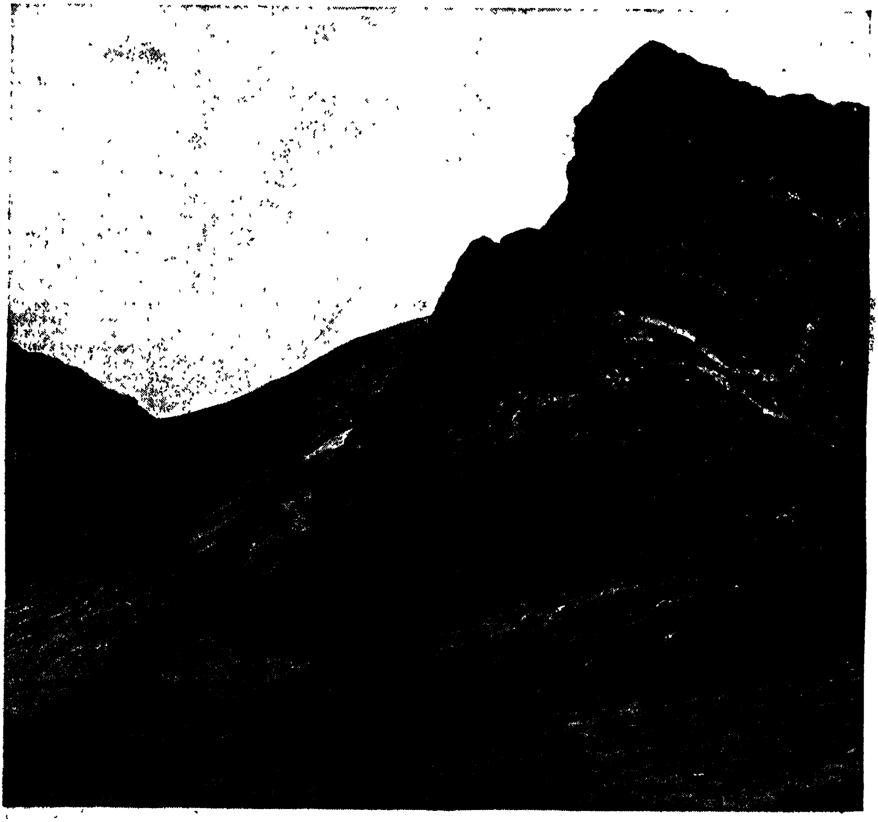

Fig. 153. Characteristically banded gneiss forming valley wall at Sperry Glacier, Glacier National Park. ***Photo by Hileman. Courtesy National Park Service.***

Anthracite (Chapter 9) is metamorphosed coal. It is black and shiny. If the metamorphism is severe the coal becomes *graphite* (pure carbon).

Cycle of rock formation. Metamorphic rocks are the third and last of the three groups of rocks that compose the earth's crust. The initial source of all rock material is the magma, which solidifies into igneous rock. Any rock, whether it be igneous, sedimentary, or metamorphic, may become engulfed and dissolved in an upward-moving magma, or it may be buried to such depths that it becomes potential magma, and liquefaction takes place when pressure is released. All three types of rock may become sediment through processes of erosion, transportation, and deposition. Igneous and sedimentary rocks become metamorphic rocks through the various metamorphic processes. A metamorphic rock may be re-metamorphosed by the same processes; its original identity becomes more difficult to recognize with each period of activity.

ECONOMIC RESULTS OF DIASTROPHISM

Diastrophism produces two distinct types of economic results. One is the creation, through metamorphism, of minerals and rocks of commercial value. The other is the control exerted by rock structures on the accumulation of oil, gas, and underground water, and on the position underground of other types of mineral deposits.

Metamorphic rocks of economic value. The principal metamorphic building stones are *marble* and *slate.* The value of marble depends largely upon its coloring and its ability to take a fine polish. Vermont is the principal producing state, but in spite of its availability in the United States, marble is still imported from the famous quarries at Carrara, Italy. Slate owes its value to its cleavage, which permits the quarrying of large thin slabs, and to its colors. This rock occurs among the metamorphic rocks in the eastern part of the United States, and is mined chiefly in Pennsylvania. Another metamorphic rock, *anthracite coal,* was discussed with the other varieties of coal in Chapter 9.

Commercial minerals occurring in metamorphic rocks. *Graphite* like diamond, is pure carbon, but instead of being the hardest of all known substances it is one of the softest. It is slippery and black, and will mark paper. Graphite occurs disseminated through metamorphic rocks, especially schist, and in definite veins. Where disseminated, the carbon was originally carbonaceous material, such as plant remains, but the organic elements other than carbon were volatilized and driven away by heat and pressure accompanying regional metamorphism. Where vein graphite is enclosed in sedimentary rock, and is parallel to the overlying and underlying strata, the logical conclusion is that the graphite was originally a bed of coal that was altered to graphite through intense regional metamorphism.

Graphite has been found and attempts have been made to exploit it in about three-fourths of the states of this country. However, mining has been profitable in only a relatively few localities. The leading graphite states are Alabama, Texas, Rhode Island, Nevada, and Michigan. It is found in Mexico also. The largest reserves of graphite are in Madagascar and Ceylon, and these islands are its chief producers. Graphite is made successfully in electric furnaces at Niagara Falls. More graphite is made there than is mined domestically.

Graphite owes its industrial importance to the possession of the following four properties: its blackness, slipperiness, great resistance to heat, and electrical conductivity. Graphite, because of its slippery surface, is much used in foundry facings. Powdered graphite is sprinkled over the mold so that the solidified casting can be separated from the mold without destroying the latter. At one time the leading use of graphite was in making crucibles for crucible steel. Graphite is likewise used in making crucibles for melting brass, bronze, and other alloys. The color of the mineral is responsible for its utilization in pigments, paints, and stove polish. It also has some use as a lubricant. Due to its electrical conductivity graphite is used in dry batteries and for electrodes. The so-called "lead" in lead pencils is graphite, but this is a relatively insignificant use of the mineral in terms of annual tonnage consumed.

Sillimanite is the name applied commercially to a group of aluminum silicate minerals (one of which is *sillimanite*) that occur only in metamorphic rocks such as schists. When heated, these minerals change into a porcelain that is extremely resistant to high temperature, sudden changes in temperature, and great vibration. Thirty years ago the greatest weakness of an internal combustion engine was its spark plugs. The widespread use in recent years of sillimanite has practically eliminated engine failure due to cracking of the spark plug porcelain. Sillimanite porcelain is also used in refractory laboratory ware. The principal domestic source of sillimanite minerals is the Inyo Mountains of California. These minerals also occur in Virginia, North Carolina, and India.

One type of commercial *asbestos* occurs in serpentine as a by-product of metamorphic processes. Asbestos occurs in the United States in such widely scattered states as Vermont, Arizona, Georgia, and North Carolina. However, most of the asbestos consumed in the United States (and this country uses more asbestos annually than does all the rest of the world) is imported from large deposits in Quebec and South Africa.

The utilization of asbestos is based upon its resistance to heat, electricity, and acid. The long-fibered or spinning asbestos is woven into cloth used in automobile brake linings and clutch facings, theater curtains, and firemen's suits and gloves. If the asbestos is either in fibres too short to spin, or is in a matted condition, it is molded under great pressure into wallboard, pipe covering, and stove and furnace linings. It is also made into shingles, acid filters and other pieces of laboratory apparatus, artificial silk, and plaster designed to improve acoustic properties of auditoriums.

Another metamorphic mineral utilized commercially is *garnet*. But few garnets are gem-worthy; practically the entire production is used for abrasive purposes, as in garnet ("sand-") paper. Gneisses and schists are mined for their garnet content in New York and North Carolina.

Zinc and manganese minerals occur in a commercially important deposit at Franklin, New Jersey. The ore, called franklinite, has suffered intense regional metamorphism which has altered the metallic minerals into compounds not found elsewhere. This is an exceptionally rare occurrence.

"Traps" in which oil and gas accumulate. Once oil and gas have migrated into a reservoir rock, they continue to move through the reservoir rock until trapped. The direction of movement is up the dip, because oil and gas are lighter than the water which saturates almost all reservoir rocks. The trap which prevents further movement may be a structural condition such as an anticline or an unconformity, or it may be due to a decrease in the permeability of the reservoir rock, or even to a complete pinching out up-dip of the oil-bearing stratum. The structural traps are created by diastrophism, the other types by a combination of diastrophic movement and other factors, such as the character and extent of the original sedimentary deposit.

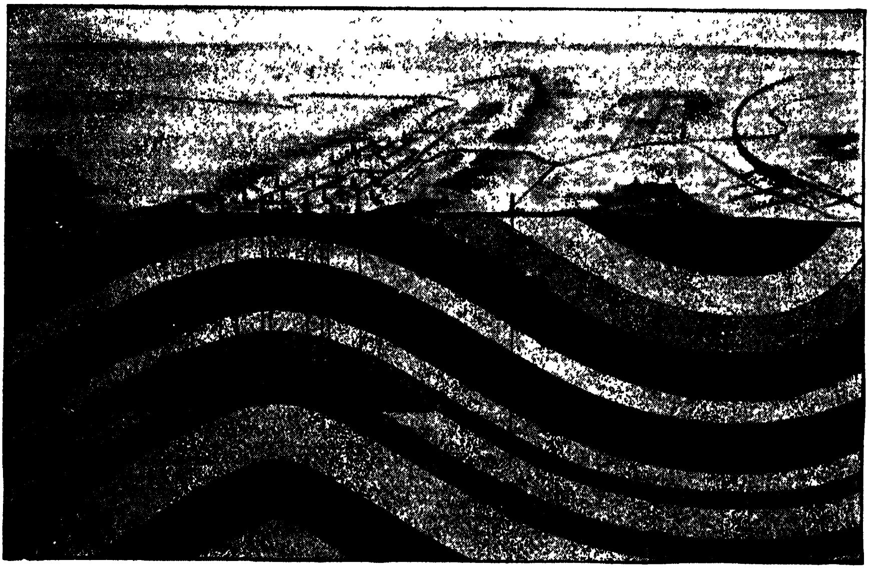

Fig. 154. The trapping of oil by an anticline. The lighter-than-water oil rises through the water-filled sandstone to top of upfold. Further upward movement is prevented by impervious cap rock. *By John Jesse Hayes.*

A trap which is capable of causing oil accumulation is known as a *closed reservoir.* This is a sandstone or other porous rock completely capped by materials impervious to the migration of oil. If a reservoir rock locally dips in opposite directions from a common point, producing an anticline, the reservoir becomes closed and oil migrating up either flank of the fold will be trapped beneath its arched roof (Fig. 154). Domes are anticlines in which the strata dip away in all directions from a high point. Some oil-producing domes are circular in plan, but most are elliptical. A special type is the salt dome found along the coasts of Louisiana and Texas. There folding has not been due to diastrophism of the mountain-building type, but to the intrusion of a plug of salt which has arched or domed the overlying sediments. The oil associated with salt plugs may occur in one or more of three possible places: (1) in reservoir rocks arched over the top of the plug, (2) in the truncated and tilted sediments flanking the plug, the salt itself acting as an impervious barrier to further migration, and (3) in porous zones in the cap rock of the salt plug (Fig. 155). Reservoir rocks may also become closed through faulting. The trap in this case is caused by an inclined reservoir rock abutting an im-

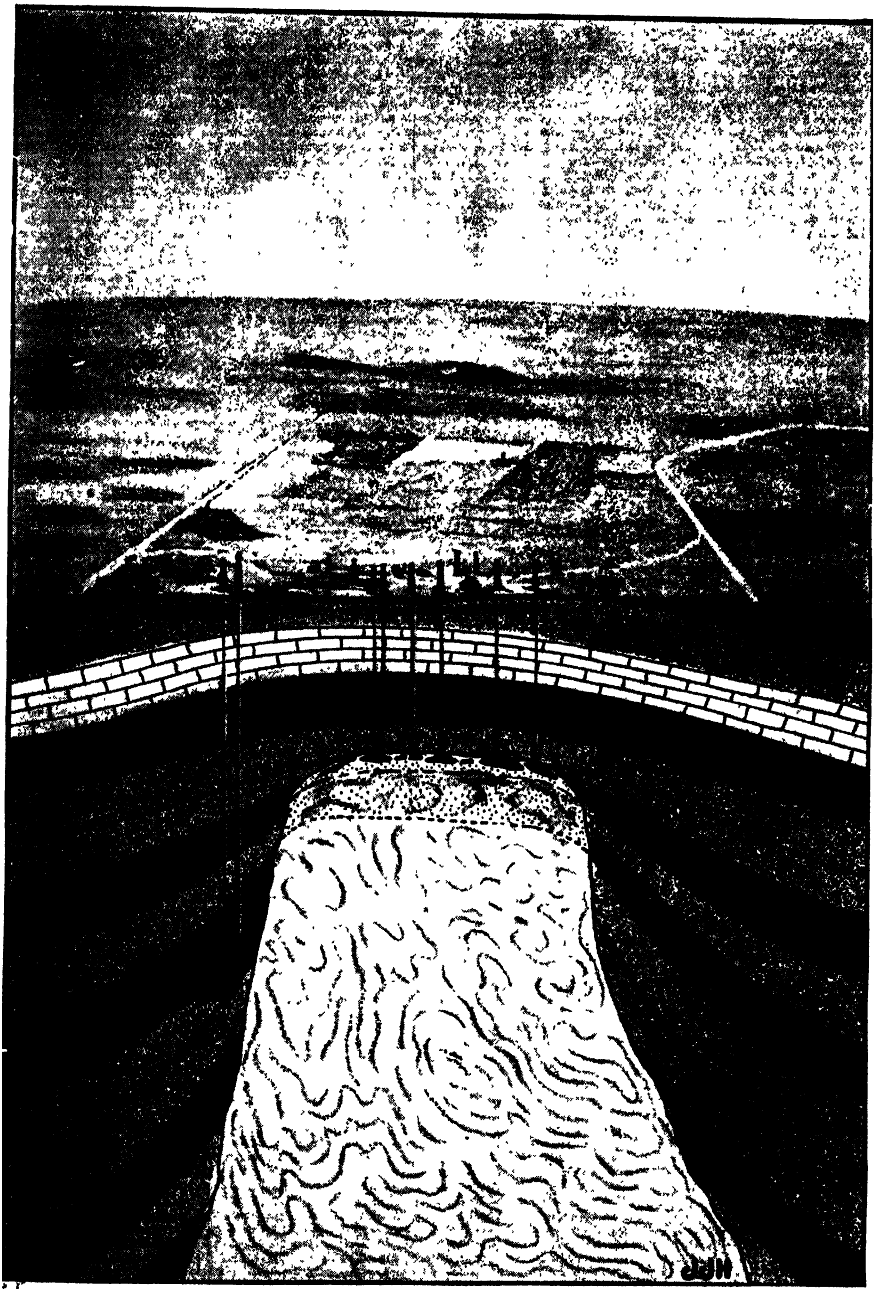

Fig. 155. Salt dome. The cylindrical mass of salt has been pushed through the layered rocks (dragging them up before piercing them), almost to the surface. Oil wells in center are producing from porous zones in the salt cap; two wells on the left tap a reservoir that has been dragged up and truncated by the salt plug. Where the salt mass did not reach so near the surface, oil may be obtained from the arched overlying strata. *By John Jesse Hayes.*

pervious rock at the fault plane. The impervious rock acts as a dam to the oil that migrates up the dip of the reservoir rock.

Relatively unimportant reservoirs are those formed through the fracturing of rocks. Oil has accumulated in fractures in shale in a few localities.

Reservoirs can be closed by varying porosity, as well as by folding or other movement of the rocks. For example, oil may migrate up the dip of a porous sandstone to the point where that sandstone wedges out. If the enclosing rock is impervious, the oil can move no farther and will become impounded below the upper end of the sand body. The greatest oil fields so far discovered produce from sandstones of this type that disappear up-dip. In some cases the porosity of the rock becomes less up-dip due either to increased cementation or to an increased percentage of shale or other fine-grained material.

A sudden change from pervious to impervious conditions may occur where folded and truncated strata are overlain by impervious younger sediments. In this case the oil moves up the dip of the tilted reservoir rock until it encounters the unconformable overlapping

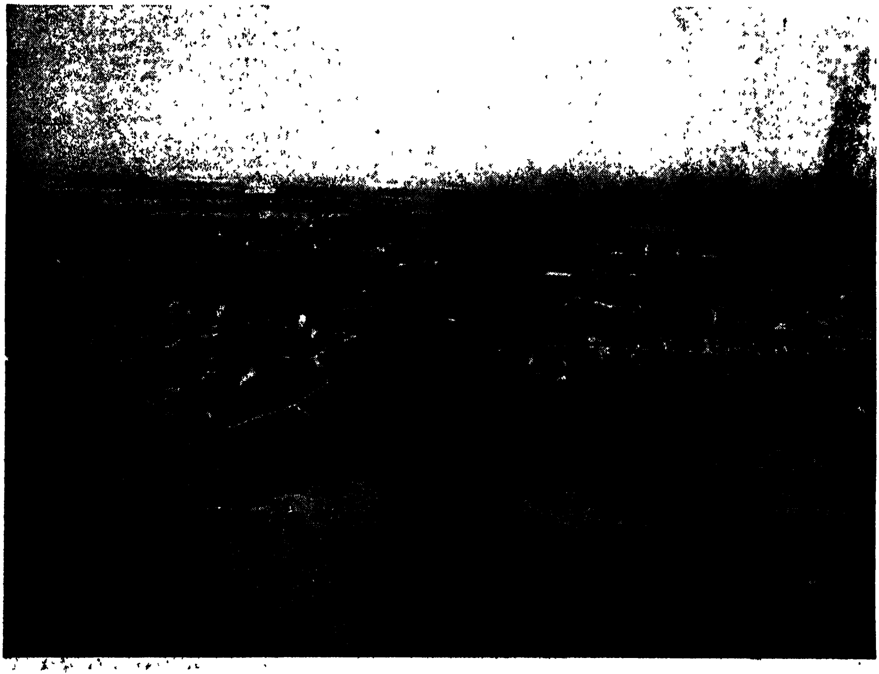

Fig. 156. Santa Fe Springs, California, oil field. Production from beneath an orange grove. Gusher in foreground is inundating surrounding countryside with oil. *By permission Spence Air Photos.*

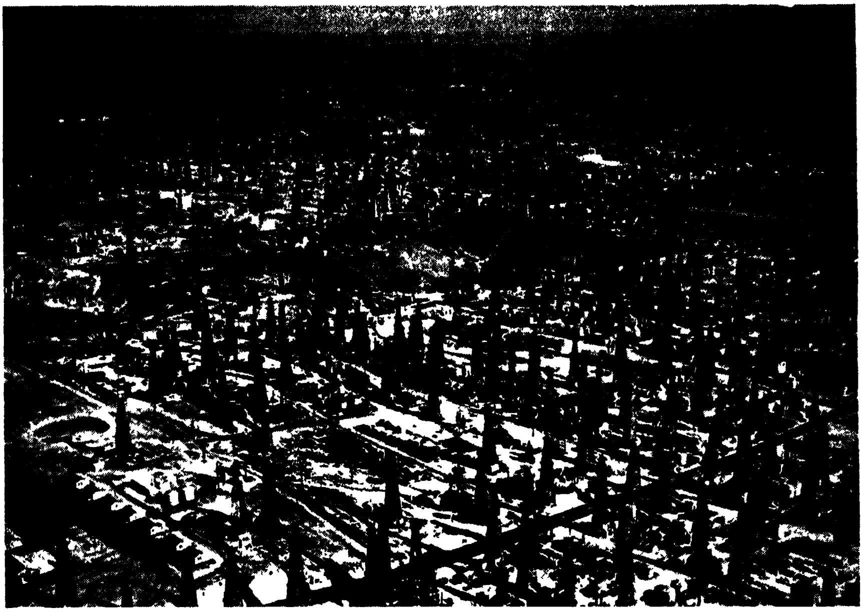

Fig. 157. How not to exploit an oil field. Closely spaced town lot drilling is exceedingly wasteful. Signal Hill, California. *By permission Spence Air Photos.*

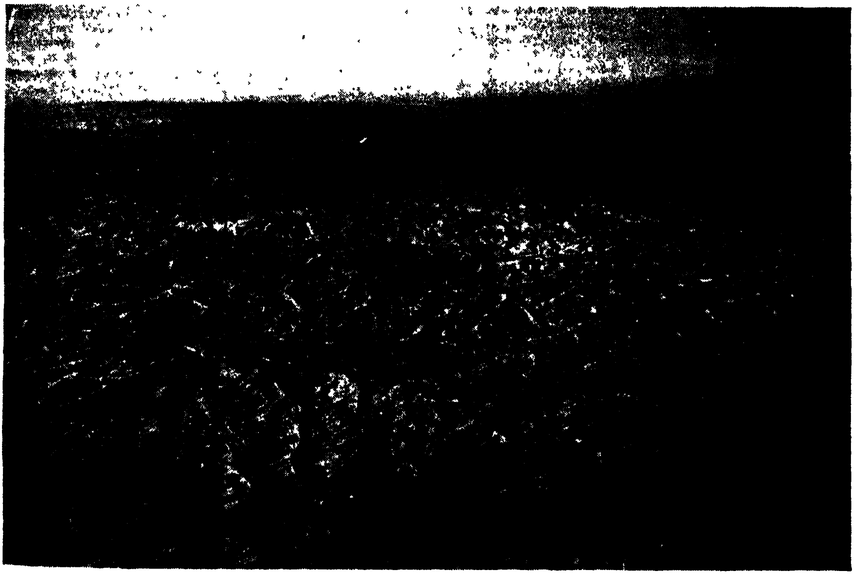

Fig. 158. Elk Hills, California, oil field. Production from beneath barren hills. *By permission Spence Air Photos.*

rocks which prevent further migration. A somewhat analogous condition is found in some of the California and foreign oil fields. There, however, the folded and truncated sediments are not covered by younger sediments, but crop out at the surface. Normally under such conditions the oil migrates up the dip all the way to the surface and becomes dissipated. But because of escape of the volatile constituents of the petroleum, and perhaps also because of chemical reactions which take place near the surface, the seeping oil tends in time to become asphalt, a relatively impervious solid hydrocarbon. Eventually asphalt may so clog the pores at the surface that further escape of oil is impossible, and oil begins to accumulate below the asphalt barrier.

Local accumulation of oil in all of the commercial fields in the world has been due to one or more of the structural conditions just

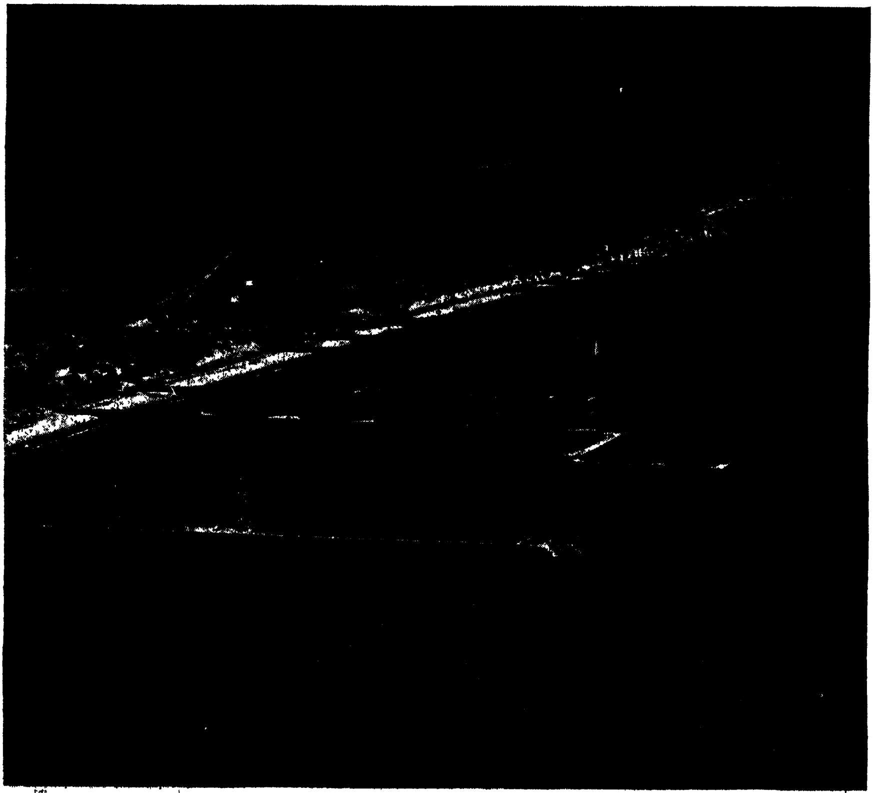

Fig. 159. Oil wells that go to sea. A part of the Elwood, California, oil field lies beneath the waters of the Pacific. Some Gulf Coast oil fields are entirely off shore. *By permission Spence Air Photos.*

outlined (Figs. 156, 157, 158 and 159). The search for and recognition of these favorable structural conditions is the province of the geologist. The structure of the sedimentary rocks over thousands of square miles of the earth's surface has been mapped by petroleum geologists. The methods pursued will be discussed in Chapter 17.

Other effects of rock folding and faulting. The movement of water through stratified rock is likewise controlled by structural conditions. Artesian pressure is due to water entering an inclined porous stratum. The direction of flow of water in confined aquifers (pervious beds sealed above and below by impervious strata) is down the dip. Therefore the ground-water geologist must pay particular attention to the bed-rock structure.

Rock structure is important to the miner also. Where diastrophism has occurred after a mineral deposit was formed, the deposit will be folded and faulted the same as the enclosing rock. For example, coal beds may occur in folded regions. Mapping the structural geology of the associated rocks may lead to the discovery of areas where the coal lies near the surface and may also give information as to the depths to the coal in synclinal areas. In order to follow a folded mineral deposit underground, it is likewise necessary to know the structural geology, especially where faulting cuts across a bed or vein. Where an ore vein is deposited after diastrophism has taken place, the structure of the rocks may determine the pathways followed by the ore-bearing solutions. Therefore, structural geology can also be used as an aid in the discovery of some types of mineral deposits.

PART THREE

Beneath the Crust

The preceding chapters have dealt mainly with geologic processes. These processes operate largely at or close to the earth's surface, and the statements made concerning them have been based upon direct observations. Now we turn to the rest of the earth, the four thousand miles from the outermost skin to the center. Obviously this study cannot be based upon visual observations, but indirect observation and inference will be used instead. We must assemble all available information concerning the earth's interior before proceeding to Part Four, "Earth History," for this knowledge is essential to the study of the earth's earliest history, or origin.

CHAPTER 12

The Earth's Interior

OUR DEEPEST CANYONS CUT INTO THE earth for distances of over a mile. The deepest mines permit men to penetrate beneath the surface for a distance of about a mile and a half, and the deepest oil well (at the time that this is written) has made available records down to a depth of slightly over three miles. We have, nevertheless, a surprising fund of information concerning the earth far below those levels. Some information has been gained by a study of the other astronomic bodies, especially the meteorites which are incessantly "pelting" this planet. Geodetic observations regarding the shape of the earth give us clues regarding the past conditions of the material composing the earth. Geologic observations made at the earth's surface furnish a number of clues concerning the character and behavior of the rocks at depths far beyond those attainable by man. Of great value have been the geophysical data concerning the density of the earth, the compressibility of rocks, and especially the behavior of earthquake waves as they pass through the earth. This chapter describes various observations that bear upon the earth's interior, and it ends with conclusions that these various data make possible.

Astronomic observations. The earth is but an infinitesimal part of the celestial universe. This cosmos consists of millions of stars of which our own sun is one. The stars are highly heated masses of incandescent gas. Important data regarding their chemical composition have been obtained by spectrographic methods. Most of the elements which make up the earth have been found in the sun's spectrum. From this we can infer that we were once a part of the sun, and that therefore the earth was once a gaseous body.

Held to the sun by the gravitative attraction of that large body are nine planets, one of which is the earth. The planets revolve about the sun in orbits that are nearly circular. The larger planets are probably still in a gaseous or liquid state. Most planets have from one to nine satellites which revolve around them as our satellite, the moon, revolves around the earth, and in the same way that the planets revolve about the sun. Each satellite is similar chemically to the planet that controls its orbit and is probably an offshoot of that planet.

The study of our celestial neighbors leads to the conclusion that the earth was originally gaseous, and in all probability it passed through a liquid phase before becoming solid. The significance of the liquid phase will be brought out later in this chapter.

Of considerable popular interest and of great importance to our study of the composition of the earth are *meteors* and *meteorites.* Meteors are celestial bodies too small to have definite orbits about the sun, as do the planets. Instead, they wander through space and, if they get sufficiently close to a planet such as the earth, are captured through the superior gravitative attraction of the larger mass. The speed of a meteor entering our atmosphere produces friction which turns the meteor white-hot, and the vast majority of meteors are completely consumed before reaching the earth's surface. Those that do survive are reduced to but a fraction of their former size and are called meteorites. The largest meteorite so far discovered weighs several hundreds of tons, but the smallest are little more than particles of dust.

Meteorites can be classified in three types. One type is composed of an alloy of iron and nickel (mainly the former), and will take a polish like any other metallic substance. These meteorites are quite different from rocks found on the earth's surface both in composition and density. However, we shall see later that the core of the earth is comparable in density to the metallic meteorites. The second type is the stony meteorite, which is composed of interlocking crystals of non-metallic minerals. These are silicates of magnesium, iron, aluminum, and other elements. The stony meteorites do correspond in appearance and composition to some of the dark-colored igneous rocks found on the earth's surface. The third type of meteorite is a compromise between these two extremes, consisting of a mixture of irregular masses of iron-nickel alloy in a surrounding ground mass of silicate minerals.

Meteorites interest us because they indicate the type of material composing the solid bodies in the solar system. They consequently give us clues as to what the composition of the earth's interior may be.

Geodetic observations. Geodesy is the science that deals with the shape of the earth. Accurate surveys have shown that our globe is not a true sphere, for its polar diameter is about twenty-seven miles shorter than its equatorial diameter. In all probability the explanation of this difference lies in the centrifugal forces, set up by the rotating earth, which cause it to bulge slightly at the equator.

Geologic observations. The character of the outer part of the globe can be determined by geologic observation. In addition, studies made of the behavior of rock magmas result in conclusions that are applicable to the conditions of the earth as a whole when it was a liquid sphere.

Geological observations made at the surface can be extended downward in certain instances. For example, where granite occurs in regions of great topographic relief it extends below the deepest exposed levels; therefore all granite is assumed to have considerable thickness. Furthermore, large-scale diastrophism has brought to the surface rocks which at one time have been buried to considerable depth. Volcanic activity also brings to the surface materials from deeper levels, thus giving us some indication as to what lies beneath the surface.

From geological explorations, mine and bore-hole data, and in part through supposition, it has been estimated that the outer ten miles of the earth consist of 95 per cent rock of igneous origin and only 5 per cent sedimentary rock. By far the greater part of the igneous rock is granite or granite gneiss. These rocks not only cover many thousands of square miles of surface, but also, as deep drilling for oil and gas has shown, form the "basement" rock in many areas where the surface consists of sedimentary rocks.

It should be noted that these observations concerning the preponderance of granite have been made solely on the continents, and the continents include only one-fourth of the earth's surface. Presumably the same conditions exist beneath those parts of the continental platforms which lie beneath the oceans, but that still leaves two-thirds of the earth's surface, covered by the ocean basins, to which these conclusions do not necessarily apply. As a matter of fact, the ocean basins show no evidence of containing any granitic rocks, although opportunities for direct observation are few. Islands furnish the only good opportunity to examine the rocks occurring in the ocean basins. Instead of being composed of granite, these islands consist of dark-colored basaltic lavas. Even many of the coral islands have been found to consist of reefs capping submerged volcanic cones. Furthermore, the ocean basins have been scenes of volcanic activity during historic time, and in every instance the magma brought to the surface has been of basaltic or allied type.

A logical conclusion to draw from these facts is that the continents are underlain by a granitic crust and the ocean basins by a basaltic crust. But the continents also have had volcanic activity, and most of the eruptions have been of basaltic materials, Therefore, the conclusion is that volcanic conduits all over the world, whether they be on the continents or in the ocean basins, have access to basic magma which upon consolidation becomes basalt or allied rock. Furthermore, seismological evidence, to be discussed later, leads to the belief that the granitic shell extends under the Atlantic and Indian Oceans but is absent beneath the Pacific and possibly the Arctic Oceans. The shell is only about half as thick beneath the Atlantic and Indian Oceans as beneath the continents, however.

From geologic observation and seismologic evidence we conclude that the uppermost layer in the earth's crust is a discontinuous shell of granite, overlying a continuous substratum of basaltic rock.

One other geological observation may be applicable to the conditions existing in the earth's interior. The examination of thick sills of igneous rock has shown that as a general rule the heaviest minerals lie toward the bottom of the intrusion and the lighter minerals toward the top. Obviously the sorting took place as the minerals crystallized out of the magma, the heavier ones sinking in the magma, the lighter ones rising. The process by which this crude density stratification is produced is known as magmatic differentiation. It is not unreasonable to infer that this process may also have taken place while the entire earth was still molten, and a density stratification was the result.

Geophysical observations. A geophysicist is one who studies the physics of the earth. It has been found through astronomical observations that the average density of the earth is 5.52; that is to say, the earth is five and one-half times as heavy as an equal bulk of water. This is interesting information, for the average density of rocks available to us at and near the surface is only 2.7, and no ordinary rock has a density much above 3. Therefore, in order to make an average density of 5.5, the material toward the center of the earth must be considerably denser than 5.5. It is thought that at the center of the earth the density may be as much as 9 times that of water.

This concept of an increase in earth density inward has other evidence in its favor. The astronomers have determined the moment of inertia of the earth, and from this have determined that, unlike a flywheel, which is heavier on the rim than at the center, the earth is much heavier at the center than it is about the periphery.

Two explanations have been advanced for the increase in density between the surface and center of the earth. One of these is that squeezing of rock into smaller volume by the weight of overlying material results in a greater density closer to the earth's center. This is an ingenious theory, but experiments on the compressibility of rocks under pressures comparable to those deep in the earth make this explanation untenable. Intense squeezing does result in an increase in density, but the amount of the increase is relatively negligible. Earth pressures are sufficient, however, materially to increase the rigidity of rock. The earth as a whole is as rigid as steel, and seismologic evidence shows that between the surface and the earth's core the rigidity increases steadily. The rigidity of rock under pressure has been proven experimentally.

There remains the second explanation for the increase in density between surface and center of the earth. This postulates the presence of heavier material, such as metal, in the earth's core. The most intelligent guess that we can make concerning the identity of this metal is that it is iron. Although not abundant at the earth's surface in metallic form, iron is nevertheless the fourth most common element in the earth's crust. Furthermore, it is the dominant constituent of meteorites which, like the earth, are composed of cosmic material. It is probable that nickel is alloyed with this iron in approximately the same proportion as in metallic meteorites.

Seismologic observations. Earthquake waves were described in Chapter 11, but it was not pointed out there that the velocities of the waves vary with the kinds of rock encountered. From laboratory measurements made on different types of rocks, it is possible to calculate the velocity with which earthquake waves would pass through those rocks. Therefore, from the time it takes an earthquake wave to pass from point of origin to the seismograph on which it makes its record, the velocity can be determined, and from it information can be gained concerning the types of rock traversed.

By studying the records, or seismograms, of thousands of earthquakes which have sent waves through all parts of the earth, it has been found that at a number of levels within the earth an abrupt change in wave velocity takes place. These concentric zones of velocity change are referred to as "discontinuities," and it is natural to assume that they designate a place where a change in rock density and type occurs.

Seismologists have found two major discontinuities in the earth. The upper one lies at a depth of about thirty miles. As the waves, travelling at about 5½ kilometers per second, get down to this level, they speed up to a velocity of about eight kilometers per second, which is about what one would expect in an ultra-basic rock. Ultrabasic rocks contain more iron and magnesium and less silica than basic rocks, such as basalt. They are relatively scarce at the earth's surface, but the stony meteorites are similar in composition. Apparently the thirty-mile discontinuity separates the earth's crust from an intermediate zone composed of rock similar to stony meteorites. The other major discontinuity is found at a depth of about 1,860 miles. This discontinuity separates the intermediate zone from the very dense core.

Several minor discontinuities have been found in the intermediate zone, and one in the outermost shell (or crust). The latter marks the boundary between the granitic and basaltic layers. The thickness of the granitic shell ranges from zero in the Pacific Ocean Basin to from six to eighteen miles in the continental areas.

The minor discontinuities within the intermediate zone probably mark boundaries between rocks of slightly different chemical and mineralogical composition. The earthquake waves travel faster in the inner shells, showing that those rocks are more dense. A possible explanation for this density stratification, the process of magmatic differentiation, was given in an earlier paragraph. No discontinuities have been found in the core; apparently this is a homogeneous mass.

Temperature observations. Even the ancients were aware that the interior of the earth is hot. The existence of volcanoes with their outpourings of molten lava and hot gas is sufficient evidence of this. Hot springs and geysers furnish additional evidence. Even some artesian waters which have been carried to depths of several thousand feet between intake and outlet are abnormally warm.

Actual temperature readings have been made of lava lakes, lava flows, and of volcanic gases as they emerged from their vents. Temperature readings have also been made of hot springs, and of the water in geyser tubes.

Of course, these evidences of heat within the earth are found mainly in regions of present or recent igneous activity; but the evidence of heat beneath the earth's surface is not confined to such regions. Temperature readings have been made in deep mines and bore holes. The deepest that man has penetrated in person into the earth is in the Rand gold district of South Africa, where the bottommost workings are more than 8,000 feet below the surface. It is necessary in such deep mines to put in an elaborate air-cooling system in order that the miners may be able to work. The high temperatures encountered in mine workings can be explained in part by the heat produced through the oxidation of sulphide minerals after exposure to the air; but since sulphide minerals are scarce in deep bore holes, the readings obtained by lowering thermometers into them are considered to be reliable indices of earth temperature. Temperature readings have been made in some hundreds of bore holes down to a depth of 15,000 feet. There is considerable variation in temperature gradient from one locality to another, but the average is about 1 degree Fahrenheit for every 60 feet. Therefore, the rocks at a depth of but a mile are on the average nearly one hundred degrees hotter than the rocks close to the surface. The highest temperature obtained so far was at the bottom of a 9,000 foot hole in California where the temperature was 244 degrees Fahrenheit, or 32 degrees above the boiling point of water (at surface pressure). The effect of pressure on the melting point of rock was discussed in Chapter 10.

No one knows how hot the center of the earth is. It obviously would be hazardous to extrapolate (extend) downward to a depth of 4,000 miles the rate of temperature increase obtained by measurements in the outermost three miles of the earth. As a matter of fact, many geophysicists believe that the rate of temperature increase diminishes downward.

The reason for the internal heat of the earth is a subject of interesting speculation. According to the previously mentioned theory that the earth was at one time a highly heated mass of gas which has cooled and contracted into its present size and condition, the heat is residual, and the earth is continuing to cool and contract. This is a favorite explanation for the world-wide diastrophic revolutions which resulted in local crustal shortening by folding and overthrust faulting.

Conclusions. From knowledge obtained, by astronomers, of the celestial universe and especially of our solar system; from a study of meteorites which are samples of cosmic material; from knowledge obtained regarding the shape of the earth, its moment of inertia, density, and internal temperature; from studies made of rock compressibility; from observations made of gravitative differentiation of magmas intruded into thick sills; from geologic observations of continental granites, and of both oceanic and continental basalt flows; and from the records made of thousands of earthquake waves which have travelled through the earth, we are able to reach the following theoretical conclusions:

(1) The earth was once gaseous and then liquid before becoming solid.

(2) The earth is composed of a core surrounded by concentric shells of material of decreasing density. It has the rigidity of steel.

(3) The core is 4,200 miles in diameter and its periphery lies at a depth of about 1,830 miles. It is homogeneous and has a density about nine times that of water. As to whether it is liquid or solid is still open to question. The most intelligent guess regarding the composition of the core is that it consists of iron, probably with some nickel, similar to iron meteorites.

(4) The intermediate zone is about 1,800 miles thick, with its periphery only about 30 miles below the earth's surface. It consists of several shells. This zone is thought to consist of ultra-basic igneous rocks, similar in composition to the stony meteorites.

(5) The crust averages about 30 miles in thickness. It is divided into two shells. The lower one, which completely girdles the globe, is basaltic. The outer or granite shell is not present in the ocean basins. Over the continents it ranges in thickness from 6 to 18 miles.

(6) Superimposed in places upon the granite shell is a relatively thin and insignificant veneer of sedimentary rocks, lava flows, and mantle.

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PART FOUR

Earth History

One of the most fascinating branches of Geology is Historical Geology, in which the history of our planet and of life is deciphered, mainly from evidence contained in the rocks of the earth's crust. The following chapters discuss the origin of the earth, which is largely conjectural, the physical history of the earth, and the development of plant and animal life from their simple beginnings to the relatively complex forms of today. . .

CHAPTER 13

Origin and Age of the Earth

ALL OF THE LEADING HYPOTHESES OF earth origin can be classified in two groups: (1) nebular hypotheses and (2) tidal disruption hypotheses. A *nebula* is a great cloud of celestial matter in gaseous form. Tidal disruption is a tearing apart through tidal forces. Both groups of theories attempt to explain the origin of the entire solar system, and both accept all of the members of the solar system as having once been a part of the same celestial body. The essential difference between the two sets of hypotheses is that, in the nebular theories, the action that takes place is mainly that of shrinkage, so that the orbits of the planets occupy space formerly filled by the sun, or in reality its ancestor, the nebula, whereas in the tidal disruption hypotheses, the members of the solar system have been pulled out and away from the sun and follow orbits through space which were never occupied by the sun.

THEORIES OF EARTH ORIGIN

The leading nebular hypothesis, the Laplacian, was universally accepted for a period of about 100 years, the span of the nineteenth century. Now, for reasons which will be considered shortly, it has been abandoned. It is described here because of its ingenious character and historical importance. Although tidal disruption theories succeeded the nebular hypotheses as possible explanations for earth origin, the astronomers have become quite skeptical concerning them, but have not advanced any acceptable substitute theories.

Nebular hypotheses. Nebular hypotheses are based upon the astronomical fact that in our solar system the planets revolve about the sun in the same direction, following nearly circular orbits which lie almost in the same plane. The French philosopher, Laplace, published in his nebular hypothesis in 1796 forty years after

Immanuel Kant, the great German philosopher, had evolved the first nebular hypothesis. The Laplacian hypothesis was the first to gain universal acceptance because it was in accord with astronomical facts and physical laws known at that time.

According to the Laplacian hypothesis, the space now occupied by the entire solar system was originally a rotating nebula composed of intensely hot gas. Loss of heat caused contraction of the nebula which in turn caused an increase in speed of rotation. The increase in speed was accompanied by the formation of ring-shaped bulges around the equator of the nebula. The three concentric rings which surround Saturn were used by Laplace to illustrate his hypothesis. Eight rings were eventually squeezed off the nebula (the ninth planet, Pluto, had not been discovered at the time this hypothesis was evolved). One by one the rings broke and gathered together in spherical masses which cooled, contracted, and, in the case of the smaller planets, liquefied and eventually solidified. Thus were the planets formed. After the eighth ring was squeezed off, the nebula continued to cool and contract into our present sun.

The satellites were born from the planets in the same way. Before each planet solidified, it squeezed off from one to nine rings which became the "moons" of that planet. The three rings of Saturn are considered to be potential satellites which have not yet completely formed.

Astronomical discoveries during the last few decades have necessitated the complete abandonment of the nebular hypotheses. For example, it was found that two of the moons of Jupiter, and one of Saturn, are retrograde; that is to say, they revolve in an opposite direction to that followed by the other satellites. In no way can this retrograde movement be fitted into the nebular idea. Also it has been found that the plane of rotation of the sun does not coincide with the plane of the planetary orbits, as it should, had the planets been squeezed off from the sun's equator. A number of other important objections to the nebula hypotheses could be cited.

Tidal disruption hypothesis. In the closing years of the last century when the Laplacian hypothesis was being seriously weakened by new astronomical discoveries, two Americans, Chamberlin and Moulton, formulated a "planetesimal" hypothesis. Included in this hypothesis was the concept of tidal disruption of the sun.

Within a few years the tidal disruption hypothesis became the leading theory of origin of the solar system, a position which it still holds.

Tidal disruption of the sun was brought about through the gravitative attraction of another passing star. Although astronomers state that the chances of one star passing close enough to another to cause tidal disruption are extremely small, yet such an "accident" had to happen only once to produce our solar system. Tidal effects are felt on both sides of a sphere, so disruption took place both on the side of the sun toward the passing star and on the opposite side. The different tidal eruption hypotheses vary in the physical state of the material pulled out of the sun and the manner in which it accumulated into planets, satellites, and other members of the solar system. The best known tidal disruption hypothesis (in the United States, at least) is the planetesimal, which will be briefly sketched in the following paragraphs.

Planetesimals are bodies in our solar system considerably smaller than planets, but behaving like planets in that they have definite orbits. The passing star pulled "knots" of gas from the sun. The eruptions were pulsatory because of the viscous resistance of the sun mass. The knots or bolts changed from gas to liquid to solid almost instantly due to the intense cold encountered. The large knots were embryo planets, and the smaller knots were embryo satellites. Still smaller particles pulled out from the sun were planetesimals. All were given orbits about the sun through the continued but diminishing attraction of the passing star. The planets and satellites grew to their present size by gathering up the much smaller planetesimals while following their orbits about the sun. The incessant bombardment of the planetesimals raised the temperature of the earth and produced the interior heat which we know to be present. Temperatures sufficiently high to liquefy the rocks were locally produced, so constant igneous activity was taking place while the earth was growing from its embryonic condition to its present size.

Several objections to the planetesimal theory have been raised. The strongest of these is that it does not adequately explain the density stratification of the earth. This objection led another American geologist, Joseph Barrell, to propose a modification to the planetesimal hypothesis in 1918. Barrell suggested that even though the "knots" pulled out of the sun became solid, subsequent bombardment by planetesimals caused liquefaction, so the earth, at the time it ceased growing, was a liquid sphere. Before it solidified to its present condition the heaver (iron-nickel) material sank toward the earth's center and the lighter material rose toward the surface.

Two British scientists, H. Jeffreys and the late Sir James H. Jeans, have suggested that the tidal disruption of the sun produced two long arms of gas instead of knots. Each arm or jet was thick in the middle and thin on the end. The ends liquefied and broke off, eventually solidifying and becoming the smaller planets. The gaseous bodies formed toward the middle of the jets remained gaseous as are Jupiter and Saturn today. The satellites were formed in the same way, by being pulled out of the planets as the orbits of the latter took them near the sun.

SUBSEQUENT HISTORY OF EARTH

Origin of atmosphere and hydrosphere. The *atmosphere* is the envelope of nitrogen, oxygen, carbon dioxide, water vapor, and inert gases that completely encircles the earth. It is not very thick when compared with the diameter of the earth. The atmosphere is held to the earth instead of being thrown off into space, because the gravitative attraction of the earth is greater than the centrifugal force. The *hydrosphere* is the discontinuous and relatively thin shell of ocean water that overlies the rocks of the earth (lithosphere) in many places. About 75 per cent of the earth's surface is covered by the hydrosphere.

The atmosphere and hydrosphere probably had the same origin. An increase of about 200 Fahrenheit degrees in temperature at the surface of the earth would produce a temperature which would still be insignificant when compared with that a short distance below the surface, and yet it would be sufficient to convert our entire hydrosphere into atmosphere. Presumably in the unknown past the reverse of this took place: the temperature dropped below the vaporization point of water and water vapor in the atmosphere became hydrosphere. Three leading explanations have been offered for the origin of the atmosphere:

(1) Not all of the planetesimals that were pulled in to the earth during its growth from the nucleus were solid. Some were gaseous, and as these were added they increased the volume of the atmospheric shell of the earth.

(2) If the earth was originally a cooling contracting gaseous globe, the atmosphere could be residual vapor which failed to liquefy and solidify.

(3) The atmosphere has been produced through igneous activity, mainly volcanism. Volcanologists have obtained samples of the vapor given off by active volcanoes and have analysed these gases. Water vapor is a predominant constituent, but the elements which compose the atmosphere are also present.

Origin of continents and ocean basins. Although the seas have encroached upon the continents many times in the geologic past, and although, without doubt, certain areas which are now submerged beneath the ocean have been emergent in the past, such submergences and emergences have taken place without serious change in the major relief features of the earth's surface. The continents are platforms which stand on the average about 3 miles above the floors of the surrounding ocean basins. The submergences have been due to a continental tilting or warping which permitted large areas to dip down beneath the level of the ocean, and thereby become covered with relatively shallow sea water. This action would not seriously affect the relative positions of the continental platforms and the ocean basins. The ocean basins were formed before the dawn of traceable geologic time and have remained in existence ever since.

In the preceding chapter the outermost shell (35 miles) of the earth was described as consisting of a continuous layer of basaltic rock, overlain in the continental areas by a veneer of acidic rocks, principally granite and granite gneiss. Although this basaltic shell is continuous, it is not consistent in thickness. It is probably over 30 miles thick beneath the ocean, and may not be over 10 miles thick beneath the granitic shell that caps the continents. The granite masses are pushed down into the basaltic layer so that they are both underlain and bordered (around the edges of the continents) by basaltic rock. A possible explanation for this will be given presently.

The presence of granite above the basalt is readily explainable through processes of magmatic differentiation. It has been found in the case of thick sills and laccoliths that the heavier constituents of the magma upon crystallization tend to sink to the bottom and the lighter constituents rise toward the top. The essential minerals of granite, quartz and feldspar have lighter densities than the essential minerals of basalt, and it is quite conceivable that, during the solidification of the 35-mile surface shell of the globe, granite could differentiate from basalt through the process just outlined. But as to why the upper lighter layer should be discontinuous leads one deeply (and fruitlessly) into the realms of conjecture.

The theory that the Pacific Ocean basin was formed through the tearing out of the moon will be described subsequently. Belief in this theory would explain the origin of our largest ocean basin but would not explain the origin of the smaller ones.

Geophysicists explain the differences in elevation between the continents and the ocean basins by the principle of isostasy. According to this principle, different segments of the earth's crust are in equilibrium (balance) with other segments; the differences in height of these blocks being explained by differences in density. In other words, the mountainous areas are high because they are composed of lighter rocks, and the continents rise above the ocean basins for the same reason. An analogy is the iceberg, which rises above the level of the sea because it is composed of slightly lighter material. However, because that difference in density is slight, most of the iceberg is submerged. In the same way the lighter granitic continents, immersed in the heavier basaltic shell, "float" about three miles (on the average) above the floors of the ocean basins, but the "roots" extend 15 to 20 miles downward into the crust.

A partial explanation of the continent and ocean basin problem was advanced a few years ago by the late Alfred Wegener, a German meteorologist. The Wegener hypothesis starts with a single large continent which formed during the solidification of the liquid globe through the coalescing of the lightest constituents. In relatively late geological time this large continent broke into several fragments which drifted apart and formed our present continents. North and South America "floated" westward and Antarctica and Australia "floated" southward and southeastward. The mountains along the west border of the Americas were formed through the resistance which the two great continental masses encountered in their westward drifting. The Wegener hypothesis has been largely rejected in this country, because of reasons that are too technical for inclusion here.

THE AGE OF THE EARTH

The historian uses a century as a time unit, whereas the geologist uses periods that are millions of years in length. The time that has elapsed since the beginning of the ancient times of the historian is insignificant when compared with the time that has elapsed since the oldest rocks of the earth's surface were formed. If the span of geologic time were represented by a yardstick, historic time would be represented by less than the thickness of a thin sheet of paper.

Many methods have been tried in an attempt to determine the age of the earth. Only one of these, the radioactive method, has yielded results of an acceptable accuracy. This is a development of the past few years. Some of the older methods will be reviewed because of their historic importance and ingenuity.

It must be kept in mind, in studying the various methods outlined, that different starting points are involved. Some astronomical theories start with a liquid globe. The radioactive method starts with the oldest exposed rocks which contain radioactive minerals. The "salt in the ocean" theory begins with the first ocean on the surface of the globe. Different starting points will, of course, produce different results. However, even when allowance is made for this difference, it will still be plain that large discrepancies exist between the results obtained by the various methods.

Rate of organic change. This method was attempted in the last century, but, as it was founded on a number of arbitrary factors, it did not prove trustworthy. It is interesting, however, as an attempt to put the concept of organic evolution to a practical use when that concept was still in its infancy. Looking back through the past we see, of course, the enormous changes that have taken place in organic life. These changes, however, can not be proved to have proceeded at a consistent rate, so this method is impossible of application. Organic change is to a considerable extent dependent upon environment, and, when there is no change in its environment, an organism has little or no reason to change its character. But when, for example, near-by mountain-building activity causes a different type of sediment to be deposited in the vicinity of an organism, it has to accommodate itself to that change if it is to continue to live in the same habitat. Another environmental change is caused by the presence of ice due to continental glaciation on nearby land. The water becomes much colder, and the organisms either have to develop thicker skins or shells, migrate to warmer climes, or give up. Land animals, such as mammals, also change relatively rapidly when a different environment is imposed. Because of its wide variation, the rate of organic evolution cannot be used as a measuring stick of the lapse of time.

Sedimentation methods. Calculations as to the age of the earth based upon the time it takes for sediments to be deposited are a by-product of the theory of uniformitarianism, which was advanced by Hutton and ably championed by Lyell in England in the middle of the last century. The major premise of this theory is that the geological processes which are at work today are the same as those which were at work in the geologic past and which produced the hills, valleys, and rocks of the present. This theory is in direct opposition to the earlier idea of "catastrophism," according to which concept a canyon, for example, was formed by the sudden crevassing of the earth's crust, instead of by the slow but persistent downcutting of a river. Those who sought to determine the age of the earth by sedimentation methods first attempted to determine how much sediment is deposited over a known period of time on the ocean floor adjacent to the continent. Observations made through a period of several centuries have shown that sediment accumulates on the Nile delta at the rate of about 3 feet per thousand years. Next, the total thickness of sediment deposited since earliest traceable geologic time must be estimated. Accurate calculations of this figure are impossible. One recent estimate was 600,000 feet. At the rate of 3 feet per thousand years the oldest rocks in the earth's crust are 200 million years in age. Other estimates obtained through the use of this method range from 3 million to 6,000 million years. One major cause for discrepancy has been the use of different figures for the rate of deposition. This may vary materially with locality and with type of deposit. One investigator claims that it takes about 450 years for a foot of sandstone, 900 years for a foot of shale, and 2,250 years for a foot of limestone to be deposited. Another cause for discrepancy is the impossibility of estimating the time that elapsed between the deposition of rock layers separated by an unconformity.

An interesting modern application of the sedimentation method has been to study varved deposits. A varve is a couplet of sedimentary layers consisting of a summer and winter layer of different shades of color and thicknesses. Varves are usually confined to lake deposited clays, and because of the rather temporary character of lakes it is impossible to use this method for an extended period of time. It has, however, been successfully applied to calculating the length of time since the glaciers last receded from northwestern Europe and from New England, and to the length of time which it has taken to deposit the Green River formation, a thick lake deposit of the western United States.

Denudation method. This method is the reverse of the sedimentation method. Its followers arbitrarily calculate the number of years that it takes to clean off a foot of rock from the continent.

This figure divided into the number of feet that it is calculated has been removed in the past would give an estimate as to the length of time during which erosion has been at work on the earth's surface. Naturally when both the dividend and divisor in a calculation are estimated figures, the quotient will not be much more than a guess.

Age of the ocean. In all probability the oceans originally consisted of fresh water. The salt (sodium chloride) now found in them has been brought in by the rivers draining the continents over a period of many millions of years. We know, with a fair degree of accuracy, how much sodium chloride is in the oceans of today. Oceanographers have calculated this figure to be 12,600 billion tons. Analyses of the water of many rivers scattered over different continents and fairly accurate estimates as to the volume of river water annually entering the sea, lead to the calculation that about 35 million tons of sodium chloride are annually added to the ocean. The total sodium chloride content of the seas (12,600 billion tons) divided by the annual increment (35 million tons) gives 360 million years as the age of the ocean.

One major assumption made in figuring not only the age of the ocean, but also the age of the crust by the sedimentation and denudation methods, is seriously open to question. That is the extreme uniformitarian viewpoint that the *rate* of geological activity at the present is approximately the same as it has been in the geologic past. Actually, however, a critical study of geological history tells us that conditions at present are not average, for during the greater part of the past the continents had been eroded to as near sea level as the minimum gradients of the draining river systems would permit. Consequently the amount of sediment, both physical and chemical, carried from the continents to the seas was at a minimum. The continents of today contain high plateaus and mountain ranges, and the rivers draining these areas are loaded with sediment due to the relatively steep gradients. Mountains and plateaus are but temporary features in geologic time. So the sand, silt, clay, and sodium chloride being carried seaward at the present time is far in excess of the amounts carried during more normal times.

Also, human activities contribute to the increased load of oceanbound streams. The cultivation of the land and the deforestation of the upland areas materially accelerate soil erosion.

Astronomical methods. A great British philosopher of the 19th century, Lord Kelvin, once calculated that it would take

22 million years for a hot molten globe, the size of our planet, to cool to its present temperature. Apparently Kelvin made some mistake in his assumptions, for his figure is far too low according to present conceptions.

Another English physicist and astronomer, George Darwin, developed the hypothesis that our one satellite, the moon, was torn away from the earth by tidal attraction of the sun 56 million years ago. The basin occupied by the Pacific Ocean is the scar from which the moon was plucked, according to the Darwin theory. It is interesting to note that although Darwin's time calculations may be open to question, his hypothesis of moon origin is quantitatively possible and is supported by some astronomers today.

Radioactive disintegration. Single atoms of radioactive elements, such as uranium, explode. This explosion is accompanied by the emission of particles, and results in the decay of the element into other elements. For example, atoms of uranium decay to produce a series of seventeen other elements, the last one of which is lead. Incidentally this lead has a measurably different atomic weight from ordinary lead. Another radioactive series starts with thorium and ends with lead.

The length of time which it takes one of these radioactive elements to break down to another element may be calculated by the intensity (speed) of the emitted particles. Physical chemists specializing in this field have developed a formula by means of which the age of minerals containing radioactive elements can be calculated based upon the mathematical ratio between the "radioactive" lead (the end product of the disintegration series) and uranium. In 1,000 million years one gram of uranium breaks down to 0.865 grams of uranium and 0.118 grams of lead. Several other methods beside the uranium-lead calculation have been developed in recent years.

In the practical application of these methods of determining the age of the earth, geologists are limited to rocks which contain minerals composed of radioactive elements. Such minerals are largely confined to intrusive igneous rocks and are by no means abundant in the earth's crust.

The radioactive methods of age determination are by far the most accurate yet developed. Apparently the rate of decay of the elements in the radioactive sequence is entirely independent of temperature, pressure, and other external conditions. Consequently, it is reasonable to assume that this rate has been no different in the geologic past than it is at present.

During the few years that radioactive methods have been in use, the ages of a great many batholiths and other types of igneous intrusions have been determined. The rocks into which the igneous rocks were intruded are, of course, older than these. The oldest rock so far determined by radioactive methods is an igneous intrusion in the district of Carelia, Russia, which crystallized 1,852 million years ago, but this rock is intruded into even older rock, the exact age of which is unknown because it does not contain any radioactive minerals which can be used for analysis. It is very probable that the oldest rocks in the earth's crust are at least 2,000 million years old. The age of the earth as a whole must remain an unanswered question. The astronomers tell us, however, that our planet is young when compared with the stars.

CHAPTER 14

The Study of Earth History

THE ORIGINAL CRUST OF THE EARTH WAS probably composed of igneous rocks which formed when the outermost portion of our molten planet had cooled sufficiently to allow the liquid material to solidify. Then the various weathering agents began to attack the igneous rock and break it up into finer and finer particles which were carried away by running water or wind and deposited as sedimentary material. The different kinds of sediments themselves are important in deciphering the history of the earth, and each one tells us something about its manner and place of formation.

LESSONS FROM THE ROCKS

When the geologist finds a bed of conglomerate that is composed of angular or sub-angular pieces of rock he knows that these materials have not been carried very far from their source. If they had been, the various fragments would be rounded. Conglomerate may be formed along a steep, rocky coast where the waves beat violently against the cliffs and detach pieces of the rock which accumulate at the foot of the slope. Rapid accumulation would not permit complete rounding of the fragments, but the grinding of one rock against another soon rounds them off. Where conglomerate has been formed from coarse rocks that were carried by streams, the geologist knows that the source of the material was some high, rocky land and that the rivers were running with considerable velocity or they would not have been able to carry such large pieces of rock. Even though the conglomerate may be found today in a flat country, the conditions at the time of its deposition can thus be interpreted. Even the nature of the rocks in the old highland source itself can be determined to a certain extent by studying the kinds of rocks that are found in the conglomerate. If the pebbles are composed largely of granite, then an old granitic highland is inferred. If some of the pebbles are made of quartzite or sandstone, or extrusive igneous rock, then those kinds of rock must have been present somewhere on the old land.

Sandstones are derived from the land, and the coarseness of the sand grains gives a clue to the velocity of the river that transported them. Sandstones that are composed of pure quartz grains could only have been derived from rocks that contained considerable quantities of quartz, such as some of the granites. The size and character of ripple marks found in sandstone may tell us something about the depth of the water and the direction of the nearest shore line. The coarsest particles of sand are always deposited nearest the shore, with increasingly finer particles farther and farther from the water's edge. Such changes often help locate the nearest land and thus the source of the sediment.

Limestones are usually deposited in warm, marine water, and, if they contain marine fossils, the origin of the rock is established, even though it may now be located high up on the side of a mountain and far from the nearest ocean. Pure limestones are sometimes found covering considerable areas and these usually mean that the neighboring shores were low, the streams sluggish, and the water clear. Pure limestones cannot be deposited near to lands from which muddy streams are flowing. Shaly or impure limestones may be deposited fairly close to the shore and, they may grade outward from the land into pure limestone.

Silts and clays are composed of exceedingly fine rock particles, and they can be deposited only in quiet water. Even a small amount of movement in the water will keep them in suspension, and therefore, they are usually deposited at considerable distance from the land source. Shales are derived from muds, and the extent and thickness of a shale deposit will tell the geologist a great deal about the conditions on the neighboring land. Black shales contain carbon, sometimes an indication of land vegetation.

The colors of rocks are very important to the geologist because they are often good indications of the climatic conditions under which the rocks were formed. There are extensive red beds in the western part of the United States, especially through Texas, New Mexico, Arizona, Colorado, and Wyoming. The red color of these shales and sandstones is due to the oxidation of iron, which probably took place in a region where very little vegetation was growing; otherwise reducing, instead of oxidizing, conditions would have prevailed. This may mean that the region was a semi-arid region, such as exists in the southwestern part of the United States today, and the streams may have been intermittent or subject to great fluctuations in volume and velocity of water. Here and there throughout the red-bed region there are small areas containing the bones of amphibians and reptiles. Such places mark the positions of water holes or permanent bodies of water. Sometimes the course of an ancient river may be traced for miles across the country merely by means of the cross-bedded sandstones that were deposited in the channel of the stream.

Great thicknesses of salt and gypsum are usually interpreted as deposits made under arid conditions in bodies of water where there were an excessive amount of evaporation and periodic inflows of water from some nearby sea or ocean to renew the supply of minerals.

Lava flows with a total thickness of several thousand feet may be seen today in the iron and copper districts of northern Michigan, and, although there are no volcanoes in that region today, these rocks are proof of intense volcanic activity in the distant past. The Devil's Tower in the Black Hills region of Wyoming is a volcanic neck that has persisted because it was harder than the immediately surrounding rock. Some of the most famous diamond mines in South Africa are located in eroded volcanic necks. Volcanism is usually found in those parts of the earth where the crust is broken or fractured to great depths by mountain-building forces. Intrusions of igneous rock such as dikes, laccoliths, and batholiths also accompany periods of diastrophism, and wherever such features are found exposed we will usually discover evidence of an old mountain range.

Great areas of metamorphic rocks, such as gneisses and schists, are evidence of regional metamorphism which is commonly found in places where the crust of the earth has been subjected to the intensive pressure that is developed when folded mountains are built. Under such conditions a black mud, containing considerable quantities of carbonaceous material, may be altered by pressure and heat into a graphitic schist. The presence of these various features enables the geologist to determine the former existence of a mountain range in a region that may be quite flat at the present time.

In any relatively undisturbed sequence of sedimentary rocks, the oldest part of the section will always be on the bottom because it was deposited first. Overthrusts may reverse the normal order, but such disturbances can usually be detected. This *law of superposition* makes it possible to determine at least the relative ages of sedimentary rocks in any section, but it does not always hold with igneous materials. Lava flows will generally follow this law, but a comparatively recent igneous intrusion may lie directly below a much older one. Where one dike intersects another, or where one igneous intrusion cuts through another, the relative ages are not so difficult to determine. Igneous rocks are sometimes found intruding sedimentary formations; in such cases the intrusions are obviously younger than the sediments, although it may not be possible to determine their precise age.

Certain non-marine sediments in the Connecticut Valley region contain both lava flows and intrusions in the form of sills. The flows were formerly on the surface, but they were later covered by sedimentary deposits. The problem is to distinguish between the sills and flows. The upper surface of the flows will usually be vesicular or porous owing to the escape of gases while the molten mass was solidifying. In the case of the sills there should be some alteration in the overlying sedimentary rock just above its contact with the sill. This is contact metamorphism.

THE GEOLOGICAL TIME TABLE

Most of the events in recent history can be put in their proper time relations, because historians know the exact year in which they occurred. However, when we go back only as far as that portion of time that is covered by "Ancient History" it becomes increasingly difficult to tell in what particular year certain events happened. It is easily understood, then, why events that occurred millions and hundreds of millions of years ago cannot be placed in any particular year and why geologists must use much larger time divisions than years when they are discussing the events of geologic history.

The eras are the longest divisions of geologic time and they are very roughly delimited. Each one, in general, attempts to take account of some great event or series of related events that are world wide in their significance. For example, the Mesozoic era is that particular division of time during which the reptiles dominated almost the entire earth; in fact, it is often called the Age of Reptiles. The beginning and the end of each era are more or less arbitrarily fixed as they appear in the time table, but actually they are poorly defined at present. Great periods of mountain building, called revolutions, which occurred at long and irregular intervals, help mark the ends of the eras. However, these revolutions are not good time markers because the building of a mountain range may take several million years and the various parts of the orogeny on the different continents may not start or end at the same time everywhere. Great periods of erosion, producing widespread unconformities, follow times of moun-

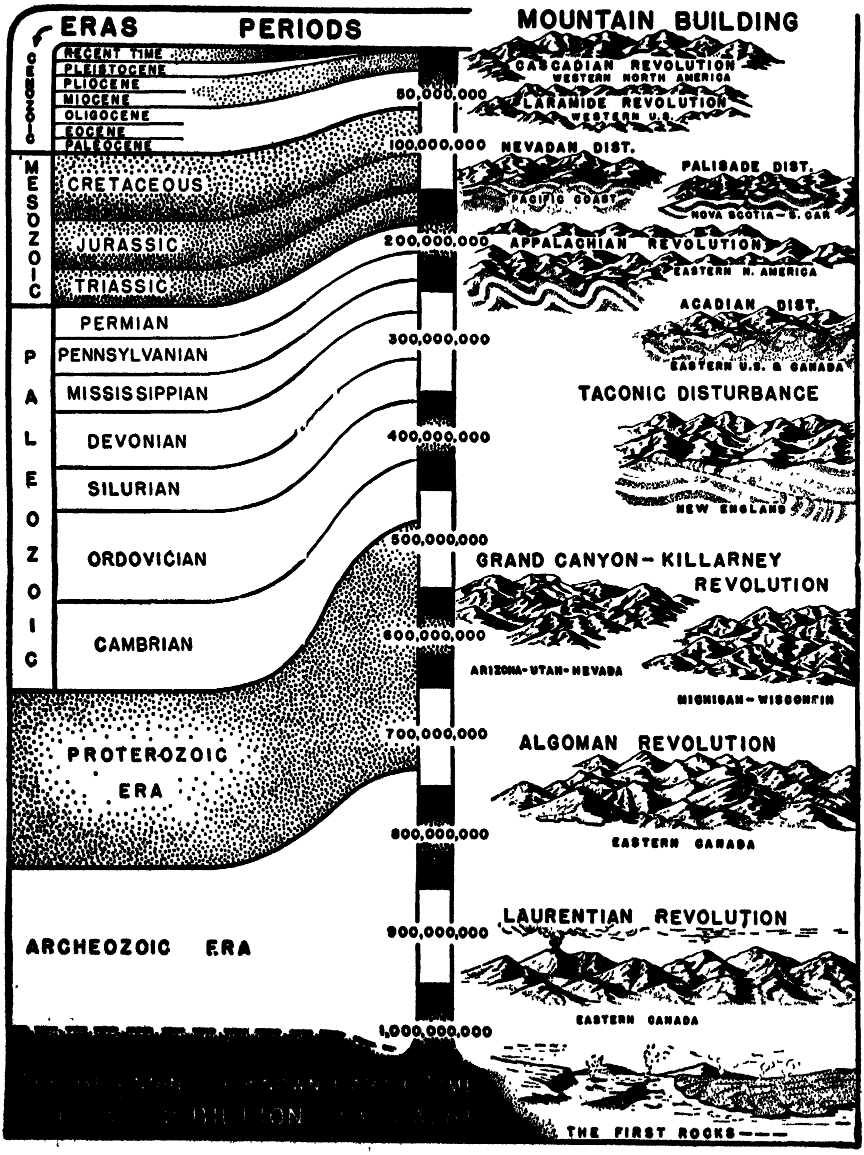

Fig. 160. The Geological Story of the Earth.

tain building. Two such unconformities help determine the close of the first two eras as they are now defined.

At the present time, five eras are recognized, but this number will doubtless be increased because, since the present Archeozoic and Proterozoic divisions are too long and unwieldy for efficient use, each will some day be divided into two or more eras.

The periods are the next largest divisions of geologic time, but even they are somewhat arbitrary in their limits. Mountain building on a scale less extensive than that of the revolutions helps determine the end of some periods; such orogenies are called disturbances. The rhythmic advances and retreats of the shallow continental seas correspond rather closely to some of the periods. The beginning of an epeiric sea invasion is thus the start of a period, and the final withdrawal of marine water from the continent marks the close of the period. Even this method has its disadvantages, because frequently there are long intervals of time between the close of one invasion and the beginning of the next one—intervals that may last for several million years. Thus, there may be great "lost intervals" in the geologic record, for much of the information upon which geologic history is based comes from the deposits and fossils left by the different epeiric seas. As our knowledge of geologic history increases, geologists will devise better methods of determining the limits of eras and periods. The time table of the future will be far more accurate than the present one—and also quite different.

All the different kinds of rocks that were formed during any geologic period are classed together under the name "system," and the rocks of any epoch are called a "series." The smaller divisions of time are also represented by rocks that are called "formations."

GEOLOGIC HISTORY IS RECORDED IN FOSSILS

Fossils are the remains of animals and plants that lived in the geologic past. Sometimes the remains consist of the original shells or skeletons, while in other cases they are impressions left in soft sediments by some part of the organism. Bones or shells are frequently petrified, by one of two methods. The original material of the hard parts may be dissolved and removed by ground water, and some other mineral, such as silica or iron, may be put in place of the original. The replacement is sometimes accomplished so minutely that every detail of the original shell or bone is reproduced in the replacing substance. In other cases the openings or pores in the original bones or shells are simply filled up with some mineral matter that is brought in and deposited by ground water. In most cases the petrified fossil is more durable than the original, and it has a good chance of being preserved indefinitely.

Unless an organism possesses hard parts (shell or bones), its chances of being preserved as a fossil are very light because of the perishable nature of flesh. However, in a few very interesting cases, the actual flesh of animals has been preserved for thousands of years. During the Pleistocene epoch, sometimes called the Ice Age, considerable numbers of animals roamed widely over the great tundra region of Siberia. Among these the Woolly Mammoths must have been very conspicuous because of their giant size. The tundra is permanently frozen to depths of hundreds of feet, and mammoths sometimes fell into frostcracks or openings in the frozen ground and were soon covered with ice. Since the temperature was below the freezing point, the flesh could not decay, and there the animals have remained for thousands of years until the present. Meandering rivers sometimes uncover these carcasses and several have been found by men who were looking for the ivory tusks that belonged to the mammoths. Thousands of these elephants lived and died in the tundra region, and their tusks have been found scattered widely over the area. The search for fossil ivory has been a very profitable business in Siberia for more than 200 years, and most of the real ivory that is used for various purposes today comes from the tusks of the extinct Woolly Mammoth. Similar finds have been made in the frozen gravel and muck deposits of Alaska, during the search for placer gold, but there the

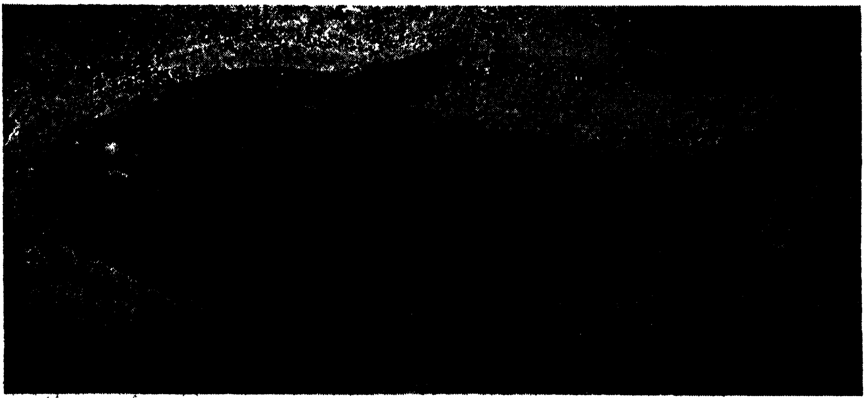

Fig. 161. A fossil fish as it was found in the Tertiary Green River formation near Fossil, Wyoming. ***Courtesy Henry P. Zuidema.***

flesh is not as well preserved as it is in Siberia. The Siberian mammoths are remarkable also for the fact that undigested food was found in the stomachs of several frozen carcasses, giving us valuable information about the food habits of these interesting mammals. In some specimens the presence of highly seasonable plants inside the stomach has enabled us to determine the approximate time of year when the animals perished.

Pieces of skin belonging to the extinct great ground sloth, Neomylodon, have been found in dry caves in Patagonia. It is possible that some of these animals lived until historic times. The skeleton and portions of the skin of another ground sloth were discovered in a guano deposit in the crater of an extinct volcano in New Mexico.

The bones of mastodons, still containing organic matter, have been found in Michigan. Carcasses of the Woolly Rhinoceros also have been found in the Siberian tundra. The carbonized skin of the extinct marine reptile Ichthyosaurus has been preserved in the fine-grained lithographic limestone near Solenhofen, Bavaria. Impressions of soft parts, especially in the form of footprints and trails, are very common, and these give us valuable information about the fleshy structures of ancient animals.

Even though an animal may possess a shell or skeleton, these cannot be preserved as fossils unless they are buried soon after the death of the organism in sediment that will protect the hard parts against weathering and erosion. There are many conditions under which an organism may be buried in some kind of protective material. Animals that live in the sea or in lakes and rivers usually sink to the bottom of the water after death. There they may be immediately covered by the soft mud, or they may be buried very soon beneath accumulating sediments. Elephants and mastodons in Michigan are preserved in bogs and swamps or even in the sediments of lakes where they were mired when they came down to the water to get a drink. Animals that die on the broad flood plains of rivers, like that which borders the Mississippi in its lower course, may be buried rapidly beneath the silt that accumulates during flood stages of the river. Dust and volcanic ash are often carried long distances by the wind and may bury the carcasses or bones of animals wherever they lie. The grand eruption of Mount Vesuvius in 79 A. D. completely buried the cities of Herculaneum and Pompeii beneath volcanic ash and mud flows. Thousands of animals, including many people, perished in this eruption, and the cities were forgotten for several centuries. When excavations began at Pompeii, numerous cavities were found in the solidified ash, some of them containing the bones of animals, although in a few cases there was merely a cavity. These openings are really the molds of the bodies of animals and people that lived in Pompeii at the time of the eruption. By pouring plaster of paris into the mold, a cast is obtained which is often remarkably life like, in some cases even revealing details of the facial expression.

The Rancho la Brea tar pits, at Los Angeles, California, are especially remarkable for the fossils that they have preserved. In this locality petroleum found its way to the surface long ago from deposits below the ground and collected in pools of various sizes. After some of the volatile constituents of the oil had escaped, a substance like asphalt remained and trapped and buried thousands of Pleistocene animals. Only the bones are preserved, but these are often in perfect condition. Skeletons of elephants, wild horses, wolves, and the great sabre-tooth cats are especially common. Some birds have also been found.

How fossils are used. Without the presence of fossil skeletons, especially those of the larger vertebrates such as the dinosaurs, our great museums would lose some of their most interesting exhibits. The cultural value of fossils is thus difficult to overestimate. Such famous institutions as the American Museum of Natural History in New York, the Carnegie Museum in Pittsburgh, Pennsylvania, the National Museum in Washington, D.C., and the Chicago Museum of Natural History are visited yearly by thousands of people who find the exhibits of fossils highly interesting. In addition to these great institutions, most universities and colleges maintain collections of both vertebrate and invertebrate fossils for many popular and scientific uses.

Fossils offer the final proof of the concept of evolution because they reveal by means of actual specimens the changes that have taken place in the animal and plant worlds for at least the last 500,000,000 years. Petroleum geologists find fossils almost indispensable in certain phases of their work. For example, it has been determined that certain fossils are characteristic of certain geologic periods or of even the smaller divisions of the periods. These are called index fossils, and, wherever they are found, they always indicate a period, or a zone within the period. Possible oil-bearing rocks may thus be located by means of the fossils which they contain. Living animals and plants, of which fossils are the dead representatives, were the original sources

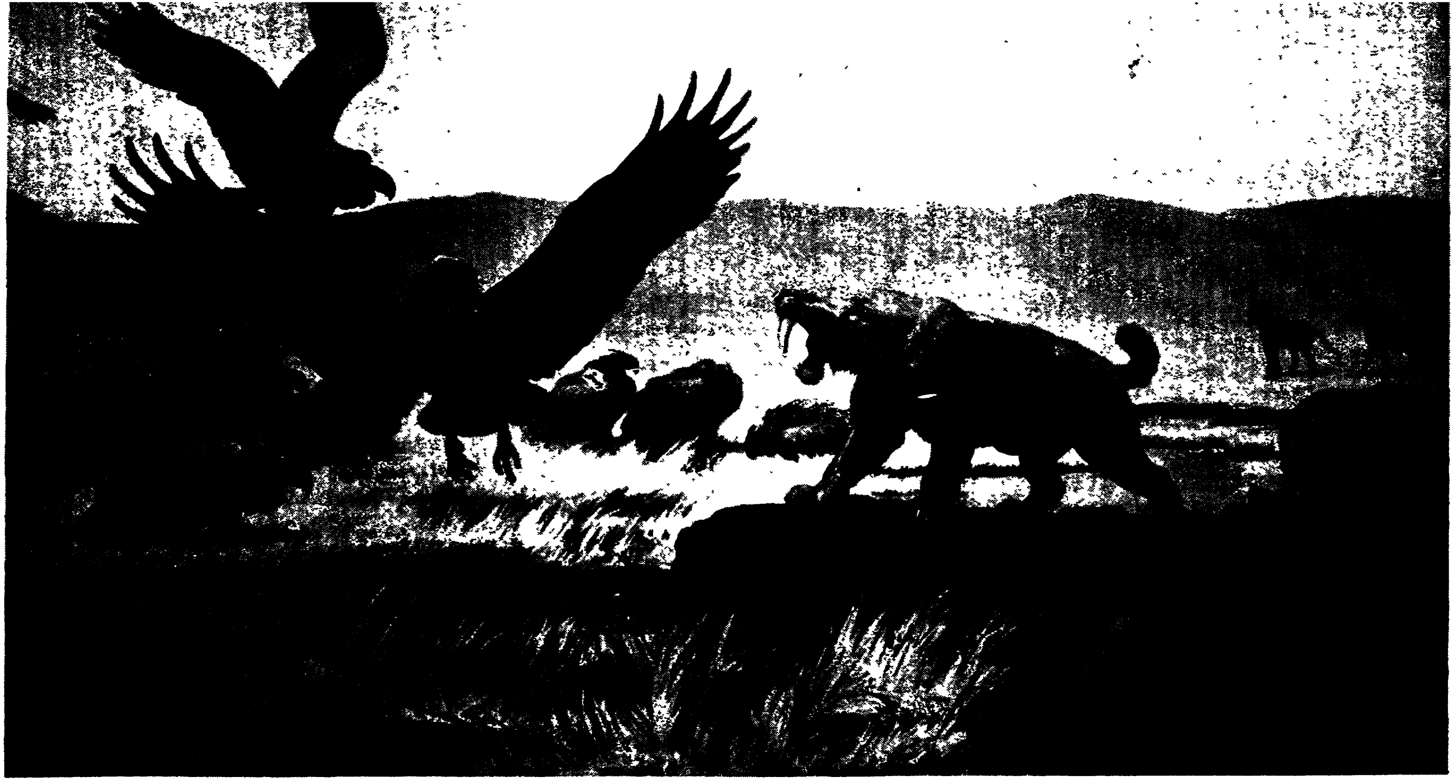

Fig. 162. A common scene in the Rancho la Brea tar pits of California. The animals shown are a characteristic assemblage of Pleistocene life of that area. The great carrion-eating vultures and other predators were trapped in great numbers as they came to feed upon animals already doomed. From a painting by C. R. Knight, *courtesy Chicago Natural History Museum.*

of most of the oil that is found today. When geologists are working out the geologic history of a region they must determine, among other things, the age of the rocks in the area and the relationship of the rocks to those in other places. Both of these problems can be solved easily whenever index fossils are found in the rocks. It is often possible to determine that widely separated rocks, even though they are several thousand miles apart, were deposited at essentially the same time, by means of index fossils that are common to the different areas. Such a determination is called *correlation.*

Many important events in geologic history have been deciphered by means of fossils. Certain organisms, such as the brachiopods and cephalopods, live and always have lived, only in marine water. If the remains of such animals are found preserved as fossils in rocks that are now far inland, or even on top of a high mountain, it is possible to say that, because the sediments which contain the fossils were deposited in the sea, those areas must once have been under marine water. Fossil plants and animals often reveal clearly the climates of the past. Certain forms are found only in the tropical zone today, and their distant ancestors also lived under the same conditions. No matter where such plants may be found in the fossil form, even though it be in the arctic or the antarctic regions, it is logical to conclude that those areas once enjoyed tropical climates. Modern reef-building corals can live only in shallow, clear marine water that is not colder than 68 degrees Fahrenheit. The fossil corals that are found in such abundance in the Silurian rocks of the northern Peninsula of Michigan indicate that this portion of the state was once covered by a clear, shallow, tropical sea.

The limestones that are used so extensively in various phases of industry were formed, in some cases, from the shells of animals, or they may represent deposits left in part by plants. Bacteria may have had something to do with some of the great iron ore deposits in Michigan and Minnesota. The graphite deposits in the Grenville series of New York and Canada offer indirect but very strong evidence of the existence of plants and animals in the Archeozoic era, more than a billion years ago.

The existence of old land bridges between continents, where no such connections exist today, is determined by the distribution of land animals and plants. Many of the same kinds of animals, such as the woolly mammoth, the mastodon, horse, and camel are found in North America and Asia. Such creatures must have migrated from one continent to the other by means of a land bridge that once connected Siberia with Alaska. Many of the islands that lie off the southeastern coast of Asia contain fossil animals that could hardly have originated on those islands but came instead from the present mainland by means of a land bridge.

Fossils are abundant in certain layers of sedimentary rocks, but whole formations may be unfossiliferous. Fossils are really quite rare objects when one considers the countless numbers of animals that have lived during hundreds of millions of years of geologic time. Only an extremely small fraction of these animals that lived in the past have been preserved as fossils. Many forms of life that formerly lived on the land or in the sea will remain unkown either because they have not been fossilized or because they are buried in rocks that are not accessible. Geologists have examined only a small percentage of the rocks that are actually exposed at the surface of the earth, but there are vast thicknesses of potentially fossiliferous rocks that are buried beneath other formations and cannot be studied. We are thus forced to conclude that our knowledge of the life of the past is very meagre, and that there are many links in the chain of evolution that may never be known.

Evidence supporting the concept of evolution. The word *evolution* is derived from a Latin word that means "an unrolling." In its simplest meaning, evolution refers to the obvious fact that animals and plants have undergone progressive changes during the course of geologic time and that the organisms of the present are the descendants of those that lived in the past. Thus both change and relationship are indicated in the word evolution. Striking evidence in support of the doctrine of evolution is obtained from three important sources: from a study of fossils, from comparative anatomy, and from a study of embryology and vestigial structures.

Paleontology, the life of the past. Since the idea of change is a necessary part of evolution, we should be able to prove that changes have taken place by collecting and studying a succession of fossils, like those of the horse family, whose history has extended through several million years of geologic time. This is precisely what paleontologists have been able to do. We now possess a very complete series of fossil forms not only for the horse, but for a number of other vertebrate groups. Because these fossil bones are the actual remains of the various animals, direct observation shows many of the changes that have taken place during the evolution of the group. It is perfectly true that paleontologists have not found every step in the evolution of all the vertebrate families, yet this failure does not affect the value of the evidence that has been discovered. The evolution of the various invertebrate groups is not so well-known, because since the earliest forms were soft-bodied, much of their essential development has not been preserved. The vertebrates appeared relatively late in geologic history, at a time when skeletons and hard, preservable parts were common.

Comparative anatomy. Relationship is also an important phase of the study of evolution, as can easily be demonstrated by directly comparing corresponding structures in the different vertebrates. The arm of a man corresponds very closely, bone for bone, with the front leg of a dog, a cat, a turtle, the wing of a bird, or in fact with the front legs of most typical vertebrates above the group of fishes. There are difference in the lengths of certain bones, and there are some modifications in the hands, but the correspondences in fundamental structures are so obvious and common that they must be the result of deep-seated relationships. It seems as though certain basic patterns were evolved quite early in the history of the vertebrates and as though these proved so successful that it was not necessary to change them except in minor respects as the various animals adapted themselves to different environmental conditions. All vertebrates have a heart and circulatory systems; all have digestive, nervous, and reproductive systems. All have skulls and brains, and these structures in skeletal parts as well as the soft anatomy cannot be the result of chance or coincidence, but must indicate actual relationship.

Embryology and vestigial structures. Embryology is a study of the individual animal before it is born. In this stage of development many structures appear that are not present or obvious in the adult, and such structures are reminiscent of a distant stage in the history of the group. Only a few examples can be given, but they present striking proof that the animals of today have descended from those of the past. In the first few days of embryonic life, every individual vertebrate of every group develops gill slits immediately back of the head, along the sides of the neck. Now gill slits have a perfectly logical explanation when they are found in the fish, because they serve as exits for the water that has passed over the gills during the breathing process. However, gill slits are not functional structures in reptiles and mammals, but they are vestigial organs in these groups. It seems clear, then, that the vertebrates above the fish group have inherited their gill slits from some remote ancestor in which they were originally functional. The geologic record supports this idea because there was a time in the history of life on earth when the highest form of vertebrate life was the fish—amphibians, reptiles, or mammals did not exist. Somewhere during the course of evolution the gills were lost and lung breathing became the habit, but for some reason that is not entirely clear, the gill slits are retained.

The well-known vermiform appendix is a vestigial structure in man; for him it has no apparent function. In fact, it is not only useless but often is a source of infection and must be removed. Many herbivorous animals possess a functional structure, the caecum, of which the appendix is the degenerate remnant. It is certain that some remote ancestor of man must have had an organ corresponding in position to the appendix, but which was functional at that time. There are three muscles around the human ear which have fallen into disuse and these muscles are identical in all essentials with those found in many other mammals which use them to move their ears. Each leg of the horse has two splint bones which are vestiges of once-functional digits which lay along either side of the central toe. The adult porpoise, a marine mammal, has only front flippers, but hind-leg buds are present in the embryo.

Vestigial structures such as these, and many others that are found in all the different vertebrates, were all functional in some ancestral animals, and they are clearly inherited from the distant past. They show that all animals have changed during the course of time. and thus they help to demonstrate the truth of evolution.

CHAPTER 15

The History of Life on the Earth

WHEN THE EARTH WAS A MOLTEN SPHERE, more than two billion years ago, life as we know it now could not exist. It is difficult for us to conceive of a lifeless Earth—nothing but heat, space, and motion. Therefore, we are confronted with the extremely difficult question of when life started and the even more puzzling problem of how it began. Even the first and simplest forms of life were probably the result of extraordinary combinations of special conditions. The earliest forms of life could have been little more than formless bits of protoplasm, and, because they had no skeletons or hard parts, there are no fossils to record their existence. There is thus no known record of the beginning of life; the record of life during those countless ages that preceded the appearance of the first fossils in the rocks is completely lost in the impenetrable obscurity of the distant geologic past.

THE ORIGIN OF LIFE

Protoplasm, which is the material out of which all living things are made, can be analyzed by the chemist and found to contain twenty-nine of the elements that are known to science. Such common substances as hydrogen, carbon, oxygen, and nitrogen are always present; they are apparently indispensable in the composition of living matter. Carbon is such a dominant element in protoplasm that it has been called the base of all life, but, in spite of the fact that scientists know the materials out of which protoplasm is made, they have never been able to discover just how these elements are combined to produce life.

Living things as they are known upon the planet, Earth, cannot exist very long in temperatures above 212 Fahrenheit degrees or below 32 Fahrenheit degrees; and the great majority of plants and animals live within temperature ranges far more restricted than these. The Earth is unique among the planets of our solar system in that it is just the right distance from the sun for the existence of life. It is very doubtful whether organisms exist on any other planet with the possible exception of Mars, and even there it is hardly possible that anything except low forms of hardy plants could live.

There is some evidence that seems to indicate that most primitive forms of life were more closely related to plants than to animals. There are creatures living at the present time that have some of the characteristics of plants as well as of animals. Naturally, such organisms are difficult to classify. Most plants possess the green coloring matter called chlorophyll, which is not present in the majority of animals. However, some plants, like the mushrooms, do not have chlorophyll, and, on the other hand, some protozoans and worms do have it. A number of plants are free-moving forms, and certain animals are fastened to more or less fixed objects. The great majority of plants get their food from the soil, the air, and the water and subsist on inorganic materials; and yet some plants are highly carnivorous.

Primeval life must have originated in the water, and it lived for millions of years in either the sea or some large body of fresh water where it was protected against the drying action of the open air, which would have been fatal to such delicate organisms. Life must eventually have reached a stage of development similar to that represented by the modern bacteria, which are extremely small and simple plants. It is possible that the living bacteria have come down to us from the distant past with comparatively few changes.

One of the most obvious characteristics of all living things is their ability to adapt themselves to the environment in which they live. In fact, all animals and plants must adjust themselves to their surroundings or they cannot survive. This adaptability is a remarkable characteristic of protoplasm in all its forms, from the simplest to the very highest types, such as man and the other mammals. When the development of plants and animals is followed through long stretches of geologic time, it is obvious that most forms become more and more highly specialized. This is especially clear when the history of a certain animal, like the horse or elephant, can be studied by means of well-preserved fossil forms. The simplest and least specialized members of a group always appear first, followed in order by others that reveal increasing complexity of structure. In all cases there is obvious adaptation to the environment, and it is clear that, as the environment changed, the animals changed to meet the new conditions. It is only the causes of these changes that are not well understood. Some people believe that the environment is somehow able to affect the individual organism directly and thus produce changes. Others believe that changes originate within the organism. Whatever may have been the causes, it is clear that great changes in organisms have occurred. All these changes, demonstrated by the thousands of fossils that represent animals and plants of past ages, are included in the general term "evolution."

No unquestioned fossils have been found in the oldest known rocks, which belong to the Archeozoic era, but there is considerable indirect evidence that some kind of life existed in that distant era. The Grenville series, which is exposed in the Adirondack region of New York and adjoining parts of Canada, was originally composed largely of limestone, and great quantities of graphite are found in the series. Limestone may be formed from the calcareous shells of animals, and certain plants are able to take calcium carbonate from marine water and precipitate it upon the sea bottom. It is also true that limestone may be formed by purely chemical methods without the help of any form of life, but the great thickness of the calcareous portions of the Grenville series indicates that the limestone is the result of some form of life. The enormous quantity of graphite in the Grenville could hardly have been produced without the help of life in great abundance and is very strong evidence for the existence of bacteria and some other forms of plants in the Grenville sea. The Archeozoic rocks also contain important deposits of iron ore which may have been taken from the water by bacteria and precipitated. A few well preserved Archeozoic fossils, either plants or animals, would be extremely valuable, and they may be found some day.

The reasons for the absence of fossils in this earliest known part of the Earth's history are not difficult to understand. The known Archeozoic formations were originally dominantly igneous, and organisms could not live in rocks when they were molten. This fact does not explain their absence in sedimentary formations, but there are two other very good reasons for the lack of fossils. Most of these ancient sediments have been so highly metamorphosed or altered by heat and pressure that all traces of any organisms that might have been there originally are now completely gone. However, there are some sediments, which have remained in a relatively unchanged condition since Archeozoic times, that have been carefully examined for fossil remains but without success. The explanation in this case probably lies in the fact that the earliest forms of life were without any skeletons or hard parts and so have not been preserved.

The absence of skeletons in the earliest forms of animal life is difficult to explain, but since skeletons are rather specialized structures it is natural to assume that they did not develop with the very first appearance of life, but evolved later after organisms had reached a slightly more advanced stage of development. Shells and skeletons that serve the purpose of protecting and strengthening the animals which possess them were not so essential to the first types of life. Many of the one-celled organisms today are still soft bodied, and they survive and reproduce in vast numbers.

BRIEF DESCRIPTIONS OF SOME IMPORTANT PLANTS

The phylum *Thallophyta* includes the most primitive plants, such as algae, bacteria, fungi, and diatoms. The algae range from minute one-celled types to larger and more complex varieties. Some forms of algae, such as the modern Halimeda, are very important agents in the formation of limestone. The familiar green scum which forms on stagnant pools of water in the summer and the green material which grows on the shady or north sides of trees and rocks in the temperate zone, are forms of algae. Some Permian limestones in Texas contain great reefs composed mostly of algae.

Diatoms build their skeletons of silica, and these collect as diatomaceous ooze in certain places on the bottoms of ocean or quiet lakes. Diatomaceous earth or diatomite has many important industrial uses. It is an important polishing agent and filtering medium and is an excellent insulating material for covering steam pipes. Matches may contain small quantities of diatomaceous earth and it is also mixed with some paints and varnishes as an inert filler. California's Monterey shale of Miocene age is composed chiefly of diatoms.

Bacteria are minute, one-celled plants, and many of them are the direct causes of diseases. Fossil bacteria are known as far back as the Proterozoic era.

The *Bryophyta* are represented by the modern liverworts and mosses; fossil members of this group have been found in Devonian rocks. The *Pteridophyta,* or ferns, are among the earliest plants that had adapted themselves to the land, although they thrive best in shady, moist places. Some tropical tree ferns grow to a height of

50 feet. The earliest known Pteridophytes are from Devonian rocks, althought the group probably originated in the Silurian. The *Arthrophyta* include the living scouring rushes. Both the modern and fossil forms have jointed stalks with longitudinal ribs. Some of the ancient types reached the size of ordinary forest trees. The *Lepidophyta* are best known from the giant scale trees of the Pennsylvanian period which reached the great height of more than 100 feet and a diameter of several feet. The club mosses are the living representatives of this phylum. The *Pteridospermophyta* are known by the common name of "seed ferns" because they reproduced by means of seeds instead of spores. Several stumps of these tree-like plants have been found still in place in Devonian rocks near Gilboa, New York. Beautifully preserved fronds from members of this phylum are found in concretions that occur in the strip coal mines of northern Illinois. The *Cycadophyta* were extremely abundant in many parts of the world during the Mesozoic era, but today they are found only within the subtropics and tropics. The modern forms are the sago palms or cycads. Many petrified stumps of fossil cycads are found in Jurassic rocks in the region of the Black Hills. The *Coniferophyta* or conifers generally have green foliage the year round, and the seeds are developed in cones. The leaves are like needles in some forms and strap-like in others. Members of this group were world wide in distribution during the latter part of the Paleozoic era. The modern *Ginkgo biloba* belongs to this phylum. Ginkgo trees are rare in the United States and are not found here growing wild. They are commoner in certain parts of China and Japan. Some of the great trees in the Petrified Forest near Holbrook, Arizona, belong to the *Coniferophyta.* The *Angiospermophyta* or angiosperms include the modern types of flowering plants and the hardwood trees. The many members of this phylum dominate the plant life of the earth today. The Angiosperms appeared first as fossils in Lower Cretaceous rocks.

THE PROTOZOA OR ONE-CELLED ANIMALS

Protozoans, both living and fossils, vary greatly in form and function. Some are so small that they must be studied by means of powerful microscopes, and others are giant creatures 2 inches in diameter. Some protozoans, of the Amoeba type, have no definite shape but change constantly as they move about; others have well defined shapes and vary only in size. Some protozoans are sedentary and move very little, but others are vigorous animals and swim about freely.

One-celled organisms have played a very important part in geologic history: Many of them have contributed their calcareous and siliceous skeletons toward the building of rocks. The great chalk deposits in England, France, and the Scandinavian countries are composed largely of the calcareous shells of foraminifera. The Pyramids and the Sphinx of Egypt are made from rock that consists chiefly of the shells of a large protozoan called Nummulites, coin-shaped animals that were used even as a medium of exchange in

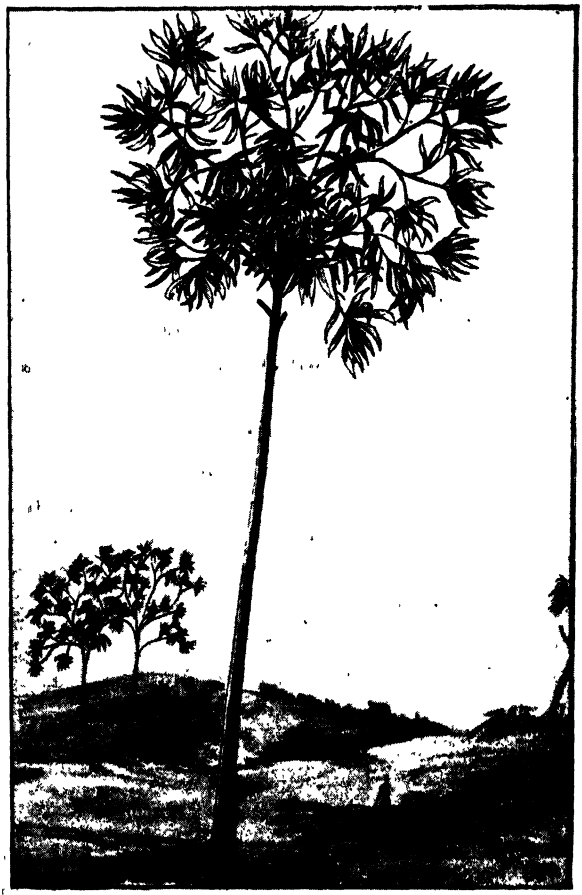

Fig. 163. Cordaites, a conifer which grew to a height of ninety feet in forests of the Pennsylvanian period. *By John Jesse-Hayes.*

some of the older civilizations. The spindle-shaped skeletons of Fusulina were excessively abundant during the Pennsylvanian and Permian periods, when they built up extensive limestone deposits in the United States, Europe, and Asia. Foraminifera are known from the Ordovician period to the Recent.

The Radiolaria build their skeletons of silica, and many of them are extremely beautiful and complicated structures. These animals live near the surface of the oceans, but after death their hard parts sink to the sea bottoms where they have accumulated over great areas as radiolarian ooze. These remarkable forms are known from the Pre-Cambrian to the present and they were very important rock-forming agents during the Tertiary period. The "Barbados Earth," which covers considerable area on the island of Barbados, is made up largely of radiolaria. The modern deep-sea radiolarian ooze is of similar composition.

THE METAZOA OR MANY-CELLED ANIMALS

The great change from animals with a single cell to those with many cells occurred during Pre-Cambrian times, but the rocks have not preserved a record of this important event in the evolution of life. The significance of this important change lies chiefly in the greater degree of specialization which the metazoa reveal. The various functions which had been performed by the single cell of the protozoan are now accomplished by several cells. This division of labor, cooperation among the various parts, and interdependence demonstrate a tendency toward increasing complexity that has been going on for millions of years as higher and higher forms of life have developed. The metazoa have evolved many very efficient types during the long course of geologic time, and in the struggle for existence these forms have done very well in general; but greater complexity of organization also presents many serious problems as keeping the various parts of the organic machine in good working order becomes increasingly difficult.

SOME IMPORTANT INVERTEBRATES

The Sponges, or Porifera. Sponges are the simplest of the many-celled animals. The majority of them live fastened to the sea bottom, although some are found in fresh water. Sponges vary greatly in shape and size, but in general they are hollow inside and have an opening at one end. The walls of the sponge contain numerous pores through which water and food material pass. Each cell of the inner portion of the animal behaves somewhat like a protozoan and takes food from the water as it passes into the hollow interior. The only sponges that have been preserved as fossils are those with siliceous or calcareous skeletons. The common sponges that are sold in many stores are merely the tough, fibrous skeletal parts of the animal, which are never fossilized. Sponges are known from the Proterozoic to the present. The skeletal elements are common in the flint nodules which occur in the great Cretaceous chalk deposits of western Europe and in Silurian limestones near Chicago.

Corals. Corals are extremely abundant animals today, and they have been even more common in the past. The typical coral animal has a barrel shaped body, with a mouth opening at the top surrounded by slender tentacles which move about and help create currents in the water, which in turn may bring food to the animal. Corals have the ability to secrete lime chiefly in the outer layers of the basal portion of the body. The animal thus lives partly inside and on top of its skeleton, which grows higher and higher as the coral continues to secrete lime.

All modern corals live in the sea. The great reef-building forms live in water that is not deeper than 250 feet and where the temperature of the water never drops below 68 Fahrenheit degrees. At the present time most corals are found in tropical waters, and, since the habits of the ancient animals were apparently the same as those of the modern forms, the presence of reef-building corals in the rocks, no matter where they are found, is assumed to be evidence of warm seas and tropical climates. Corals have been important limestone-forming agents several times during the course of geologic history, especially in the Silurian and Devonian periods. Reef-building corals have been found fossilized in regions that are cold today, and they occur even in rocks of the Arctic zone. The skeletons of modern corals are often used today for ornamental purposes. True corals are found from the Ordovician period to the present.

Worms. The members of this group are not often found preserved as fossils, although a considerable number of remarkable forms have been found in the Middle Cambrian shale of British Columbia. Their occurrence so early in geologic history indicates that they originated in Pre-Cambrian times. Numerous, very small, chitinous jaws of annelid worms have been found in the rocks.

Echinoderms. The different members of this great phylum are all marine animals with a radial symmetry. The majority of them have skeletons that are composed of numerous calcareous plates embedded in the body wall of the animal. Most echinoderms live on the sea bottom, and many of them are scavengers. They appeared first in the Cambrian period.

1. Echinoids. Some of the common names that are applied to members of this group are sand dollars, sea urchins, and heart urchins. The sea urchins are characterized especially by the presence of numerous movable spines upon the surface. Echinoderms move slowly about by means of slender distensible tube feet, with suction disks on the outer ends, which can be fastened to some object. Contraction of these tube feet then pulls the animal along. Echinoids, both fossil and recent, are gregarious animals, and they occur in certain localities in enormous numbers.

2. *Starfish* are star-shaped animals which may have anywhere from 5 to more than 40 arms which radiate from the central part of the body. The starfish has remarkable powers of regenerating lost arms. These adaptable animals are found living in the cold waters of the Arctic, and the form called *Asterias forbesi* is exceedingly abundant all along the Atlantic coast from Maine to the Gulf of Mexico. Starfish appeared in the Cambrian period but they are not very common as fossils.

3. Blastoids. These echinoderms had a bud-shaped cup composed of 13 plates arranged in a definite pattern. There was a short stem which anchored the animal to some object on the sea bottom, but arms were not developed. Blastoids lived from the Ordovician period to the Permian and were exceedingly abundant in certain localities during the Mississippian period.

4. Crinoids. These echinoderms are sometimes called sea lilies because of their plant-like appearance. The cups vary greatly in shape, and in size they range from those with a diameter of less than an inch to giant forms more than eight inches in diameter. The stem is composed of disks, like a pile of coins, and they range in length from a fraction of an inch to about 70 feet. The crinoids have flexible arms that sometimes branch several times until they are very complex structures. Most modern crinoids are free-moving animals, but the fossil forms were commonly anchored to the sea bottom by means of root-like appendages.

Crinoids are gregarious animals; they are found living in enormous numbers in some localities. Most of them live today in clear, warm, shallow water, and the fossil forms apparently possessed the same habits. Crinoids appeared in the Ordovician period and reached their climax in number and variety during the Mississippian. Certain localities, such as Crawfordsville, Indiana, and Burlington and Keokuk in Iowa, have furnished collectors with a great many well-preserved speciments, Some Mississippian limestones are composed largely of the remains of crinoids.

Bryozoa. The bryozoa are colonial animals and each individual lives in a tiny cell or cup of lime or chitin. Most of them are found encrusting seaweeds, shells, or rocks; the colony often resembles fine moss or lace. Most of the bryozoa are marine animals, although some live in rivers and lakes. They lived in great abundance during the Ordovician period, and their skeletons helped form reef-like bioherms and extensive beds of limestone. Bryozoa range from the Ordovician to the present.

Brachiopods. These marine animals build a shell that is made of two parts called valves, joined together at one end and opened and closed by means of specialized muscles. The brachiopod is usually fastened to some object on the sea bottom by means of a fleshy stalk that extends from an opening in the small end of the larger valve. Brachiopods do not grow together in the form of colonies, but great numbers may be found in certain localities where the environment is favorable. Most brachiopods live in shallow water, but some have been dredged from depths of 18,000 feet. There are more than 225 living species of brachiopods and several thousand fossil forms that date from the Proterozoic period.

The Mollusks. The mollusks include an extremely varied group of invertebrates with bilaterally symmetrical bodies covered with a thin fold of skin called the mantle. Most of them have protective external shells of various sizes and shapes. A few have an internal shell and others have lost the shell. There are more than 60,000 living species of mollusks. *Pelecypods* include oysters, clams, mussels, and many other related forms. The shell is composed of two valves which are held open by a special ligament along the hinge line and closed by powerful muscles inside the valves. The majority of pelecypods are able to move slowly about by expanding and contracting a muscular "foot" which can be extended from the open front end of the shell. A few pelecypods fasten one of their valves to some object and remain fixed throughout life. When some irritating object like a grain of sand or the larval form of an invertebrate gets inside their valves, some pelecypods, try to stop the irritation by depositing successive layers of mother of pearl around the object, thus forming a pearl. The famous Japanese pearl industry is based upon this habit that oysters, especially, possess. Most pelecypods are marine in habit, but fresh-water forms are quite common. Some varieties burrow into the mud while others even dig into wood and soft rock. Pelecypods have not been definitely identified from the Cambrian period, but they were very common in the Ordovician. Locales where they are found range from the shallow waters upon the continental shelf down to depths of over three miles.

1. Gastropods, or Snails. Gastropods usually build spirally coiled shells that vary greatly in shape and size, with the outer surface either smooth or ornamented with spines and ridges. Snails possess a definite head, and the eyes are found at the outer ends of slender, fleshy feelers which can be retracted upon contact with some object. The mouth is equipped with a band of chitin covered with rasping teeth which are used to file their way through pelecypod and even snail shells in order to reach the animal inside the shell. When a gastropod moves, the fleshy "foot" is extended through the aperture and the shell is carried along on the back of the animal. The gastropod group is a very adaptable one. They are found in the sea, in brackish water, in fresh water, and in many places on the land. Most of them are shallow water forms, but some have been dredged from depths of more than three miles. They have been found high up in the Himalaya Mountains, over 18,000 feet above sea level. The earliest gastropod fossils appear in rocks of the Cambrian period.

2. Cephalopods. The cephalopods are highly specialized invertebrates that have assumed a great variety of forms. There are more than 150 modern genera and over 10,000 fossil species. The typical cephalopod shell is conical in shape and may be either straight or coiled, usually in one plane, but often in many bizarre forms. The first part of the shell is built when the animal is small, and as the cephalopod gets larger it builds additions to the shell, each one with a larger diameter. The growing animal thus abandons the smaller portion of the shell, moves forward into the new part, and shuts off the old part by means of a transverse partition. A cross section of the shell will often show a long succession of partitions dividing the interior of the shell into a series of chambers. The famous poem by Oliver Wendell Holmes describes a modern cephalopod as "The

Chambered Nautilus." The muscular tentacles around the mouth of a cephalopod are used for grasping various objects, and some forms have sucker-like disks on the undersides of the tentacles. The well-developed eyes are usually of large size. There is a funnel-shaped tube beneath the mouth, and the animal is able to move rapidly backwards by forcing successive jets of water out through this tube. Some cephalopods can eject a dark brown substance into the water and thus form a "smoke screen" which often enables them to escape from enemies. Some of the cephalopods of the Ordovician period built straight shells over 10 feet long and were the dominant animals of their time.

The modern squid has an internal skeleton. These animals live in the ocean today in vast numbers. The ancient squid, or *belemnite,* also had an internal skeleton, of which a solid cigar-shaped portion is often found preserved in Jurassic and Cretaceous rocks. The giant squid is known to reach a length of 50 feet. The modern octopus is without a shell or skeleton. Cuttlebone, obtained from a kind of cephalopod called the cuttlefish, is used in making scouring powder, and caged birds are often given pieces of cuttlebone which they eat to obtain salts and lime. Portions of both the squid and octopus are favorite objects of food among some races. Cephalopods are known from the Cambrian period to the present.

Trilobites. These extinct members of the crustacean class built hard exoskeletons, or external skeletons, of chitin which completely enclosed the soft body of the animal. The growing trilobite periodically molted this inflexible skeleton and developed a new one to accommodate the larger animal. The modern lobster has a similar habit. A median ridge runs from the head to the tail and divides the exoskeleton into three parts. The eyes are large and compound like those of certain insects. Trilobites varied in length from less than one-half inch to over 27 inches, and most of them were probably predatory animals. Some of them developed the habit of rolling up like an armadillo, possibly for protective purposes. Tri lobites reached their climax in the late Cambrian and Ordovician periods and became extinct during Permian time.

Insects. These highly evolved invertebrates breathe air by means of special tubes located along the sides of the body. Many recent and fossil insects have wings, but the first forms were probably wingless. Insects reproduce in such incredible numbers that they are world-wide in their distribution. Although most of these remarkable invertebrates are relatively small, they are actively competing with man for the dominance of the earth. They are great carriers of diseases and often destroy vast quantities of food. Their attacks upon the human race may thus be both direct and indirect. There are more than half a million described species of insects, and the total number of living varieties is doubtless several million.

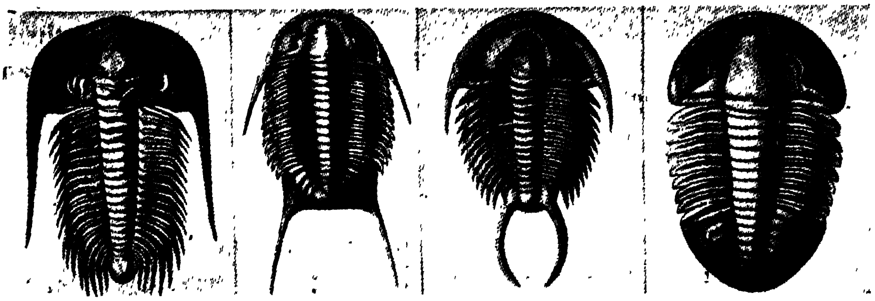

Fig. 164. Cambrian Trilobites. From drawings by *Charles Walcott.*

The bees, termites, and ants represent the climax of evolution among the insects; their success has been so outstanding that it is surpassed only by the vertebrates. The ants and bees in particular have highly developed instincts that approach the intelligence of the vertebrates in efficiency. Their social life is highly developed, and the acts of their daily lives are well regulated. The subject is so interesting that numerous books have been written about ants and bees.

Arachnids. These animals include many different types, such as spiders, scorpions, ticks, mites, horseshoe crabs, and extinct eurypterids. Some member of this group was the ancestor of the modern scorpion, which was one of the earliest land-living, air-breathing animals. Limulus, the modern horseshoe crab, is especially interesting because it has descended from ancient Jurassic ancestors almost without change.

THE VERTEBRATES

During several hundred million years of geologic history, the invertebrates were the highest forms of animal life upon earth. They had developed an enormous number of highly diversified forms, but during all those ages there was no apparent evidence that any higher form of life was evolving. However, evolution is a continuing process, and somewhere some unknown invertebrate was slowly developing the essential characteristics of the vertebrates. This unknown ancestor has never been discovered, but it probably belongs to one of the existing groups of invertebrates. It seems strange that, with all the available knowledge of fossil and existing invertebrates, the connecting link with the vertebrates has not been found, but there are doubtless many unknown fossil forms of invertebrates among the known phyla, and the problem of vertebrate origin must wait further discoveries.

VERTEBRATE CHARACTERISTICS

Bilateral symmetry is one of the obvious characteristics of the vertebrates. This means that the left half of the body is a mirror image of the right half and while the symmetry may not be perfect, still it is essentially so. Vertebrates are in general far more active than the invertebrates, many of whom show radial symmetry. The skeletons of the vertebrates are internal and are commonly made of bone or cartilage, and they serve to support the fleshy parts of the body. The backbone of the true vertebrates consists of a series of jointed cartilages or bones running along the dorsal or back side of the animal to stiffen and support the body. The majority of vertebrates have a pair of legs in front and a pair behind. Some of the exceptions are the fish (but many of these have paired fins) and animals like the snakes in which the legs have been lost by adaptation. Some of the snakes still retain vestiges of limbs. The relatively heavy bodies of the vertebrates are moved about by means of powerful muscles. The vertebrates all have a hollow spinal cord located just above or behind the backbone, which is on the dorsal side of the body. The brain is located at the front, or top, end of the great nerve cord, and is largely in control of the complicated nervous system. Special organs of sense, such as eyes, ears, and nostrils are also present. All vertebrates that live on the land, with few exceptions, breathe by means of lungs. Fish and larval amphibians breathe by means of gills. Gill slits are also found in the early embryonic development of vertebrates. These have no real function in any of the forms except the fish, but one pair becomes the eustachian tubes which lead from the middle ear to the throat.

STORY OF THE FISHES

Animals have many remarkable qualities; among these is some force that drives them on to higher and higher forms. Even though we do not know how or why the first vertebrates evolved, still this great event finally happened, and almost from the time of their appearance this new group assumed a dominant position in the life of the world. The fish were the first really great and successful group of vertebrates, and the earliest traces of primitive forms of the fish family were found in Ordovician rocks at Cañon City, Colorado. These remarkable remains occur in the Harding formation and consist of a great many detached plates and scales that once covered the bodies of lowly members of the fish family, probably the ostracoderms. No complete specimens are known, although one fairly well-preserved individual was found and accidentally destroyed. Still later other scales of the same age were found in the Black Hills, the Bighorn Mountains, and still more recently in Middle Ordovician rocks in the Northern Peninsula of Michigan. Thus the geographic range of Ordovician ostracoderms is being extended, and good specimens will probably be discovered some day. The earliest fish had no true jaws; these structures developed later from two pairs of bony rods which had previously supported a pair of gills. The rods moved into relatively horizontal positions, the front pair became fastened to the skull as upper jaws, while the second pair remained free and movable as the lower jaws. Teeth later evolved from a particular

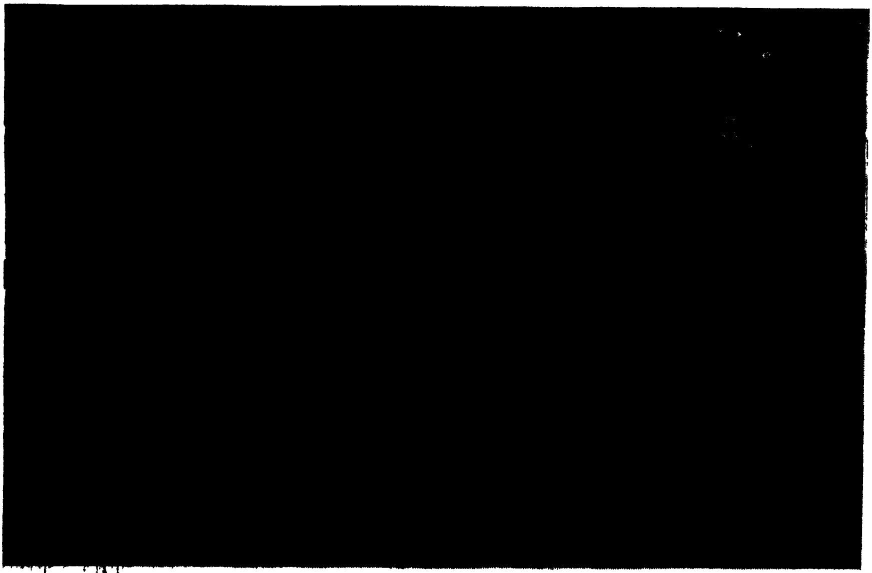

Fig. 165. CEPHALASPIS, a primitive ostracoderm fish from the Devonian. *By John Jesse Hayes.*

kind of fish scale which had a hard outer covering of enamel and a core of dentyne—the essential structure of teeth in all the higher forms of vertebrates today.

Some interesting fish. The endoskeletons of the primitive fish were probably made of cartilage. Modern sharks still retain this type of skeleton and thus reveal their ancient lineage. The dominant type of fish today has a bony skeleton. Such fish are found everywhere throughout the seas and in the lakes and rivers on the land. There are at least 20,000 species of bony fish, or teleosts, living in marine waters at the present time. The group has developed many amazing varieties, both in shape and size. The mackerel is typically spindle-shaped and is a very rapid swimmer, while the eel is greatly elongated like a snake. The electric eel has greatly modified certain parts of its nervous system so that the animal is a veritable electric battery and it is able to develop approximately 550 volts of electricity. The flounders have flattened bodies, and they lie with either the right or left side upon the sea bottom, while one of the eyes moves into position beside the other one upon the upper side of the head. The archer fish from the East Indies has a special device in the roof of its mouth by means of which it is able to eject an accurate stream of water for a distance of a few feet above the surface of the stream or pond and thus capture insects and spiders. The mud skipper is found in southeastern Asia and on some of the islands as far from the mainland as Australia. This peculiar fish comes out of the water and moves vigorously about over mud flats and even climbs up the inclined roots of trees which may be near the water. Some deep sea fish which live in complete darkness carry rows of glowing spots along their sides that light up the surrounding water.

The fishes leave the water. The most important event in evolutionary history, next to the appearance of life itself, was the emergence of certain fish from their old, limiting, aquatic environment and their gradual adaptation to a life at least partly on the land. This dramatic event required the development of certain structures, of which the two most significant were the paired limb-fins and swim-bladder lungs.

The fins of the ordinary fish are stiffened by the presence of numerous slender rods of bone, but in the Devonian lobe-finned fishes the paired fins are supported by broad bones. The difference between the fin-limbs of these advanced types of fish and the limbs of the primitive amphibians are relatively minor ones, so that we can have no serious doubts about where the land-going vertebrates obtained their paired limbs.

Many of these same lobe-finned fishes developed a double sac-like structure in the region of the chest, and a fleshy tube connected this sac to the oesophagus. The thin inner walls of this remarkable structure were roughened and corrugated and contained numerous blood vessels. Air was taken into this sac, and oxygen passed through the thin inner walls into the blood stream. Thus the lobe-finned fish was able to breathe air by means of a device that functioned essentially as do the lungs of the higher vertebrates. Many fishes of the Devonian period possessed this type of lung, which enabled them to survive in water that was unfit for fish that were equipped only with gills. There are living fishes that are air breathers, and some of them can survive for several months out of water by burrowing into the mud at the bottom of the swamp when the water disappears during the dry season.

Many of the lobe-finned fishes were therefore able to venture out of the water for a short time and move about upon the land. Their movements were not quite like those of later land-going animals, but at least they represented the first feeble attempts of the vertebrates to get out of the water and adjust themselves to a new environment. The lobe-finned fishes apparently have the distinction of being the first land-going, air-breathing vertebrates, but they were never completely adjusted to life out of the water and even the descendants of these animals, the amphibians, did not complete the adjustment to the land. This honor was reserved for the reptiles.

THE AMPHIBIANS

The evolution of the fish into the amphibian went on during the Devonian period; by the end of the period the true amphibian had appeared. The remains of these earliest semi-aquatic, air breathing animals, with legs instead of fins, were discovered in late Devonian sediments on the eastern coast of Greenland and at Scaumenac Bay, Quebec. The climatic conditions of that time must have been at least sub-tropical in Greenland or the amphibians could not have survived.

The amphibian group, just one evolutionary step above the lobe-finned fishes, are very primitive four-footed animals. Since they were the only vertebrates above the fishes from the Devonian until the Pennsylvanian period, when the first reptiles appeared, the amphibians must represent the stock from which the higher forms of vertebrates were derived.

The modern frog is a somewhat highly specialized amphibian, but its life history will serve to demonstrate the remarkable changes through which most members of the group pass from their earliest to the adult life. The eggs of the frog are comparatively small, and they have no heavy protective shell or membrane such as the eggs of the birds and reptiles possess. The eggs of the frog are laid in the water, and, because there is no yolk or food inside the egg to nourish the embryo, it emerges as a very small tadpole and goes through its larval development in the water. At first it does not even remotely resemble the later frog, but it has many of the essential characteristics of a fish and even breathes by means of external gills. No legs or lungs are present, and the animal gets its food entirely from the surrounding water. The animal grows larger, and when it approaches maturity great changes take place. The gills gradually disappear, the lungs develop, the legs are formed, and, with the final disappearance of the long tail, an adult frog emerges as the final product of a series of changes that seem to recapitulate in many respects the evolution of the fish into the amphibian. Even though the adult frog is able to breathe air and hop about upon the land, it is never a completely land-going animal. It must always protect its delicate skin against the drying action of the air, and when egg-laying time comes it must go back to the water environment of its ancient ancestor, the lobe-finned fishes. The living salamanders are not so highly specialized as the frogs and, therefore are probably more like many of the old fossil forms, especially the most primitive ones. The tail is somewhat flattened, and the animal swims by means of undulating movements of the entire body in the manner of a fish; the weak limbs are hardly better for walking purposes then the fin-limbs of the lobe-finned fishes. The lungs are not very efficient in many of the modern amphibians, and some oxygen is absorbed through the thin skin, or, in cases where the lungs are undeveloped, breathing is entirely through the skin. Some amphibians never develop lungs and so remain gill breathers throughout their lives which must therefore be spent in the water. Most modern amphibians are without scales, but some of the extinct forms had bony scales similar to those of the ancestral fish. There are also a few limbless amphibians that are nearly blind and. with their burrowing habits, resemble large worms.

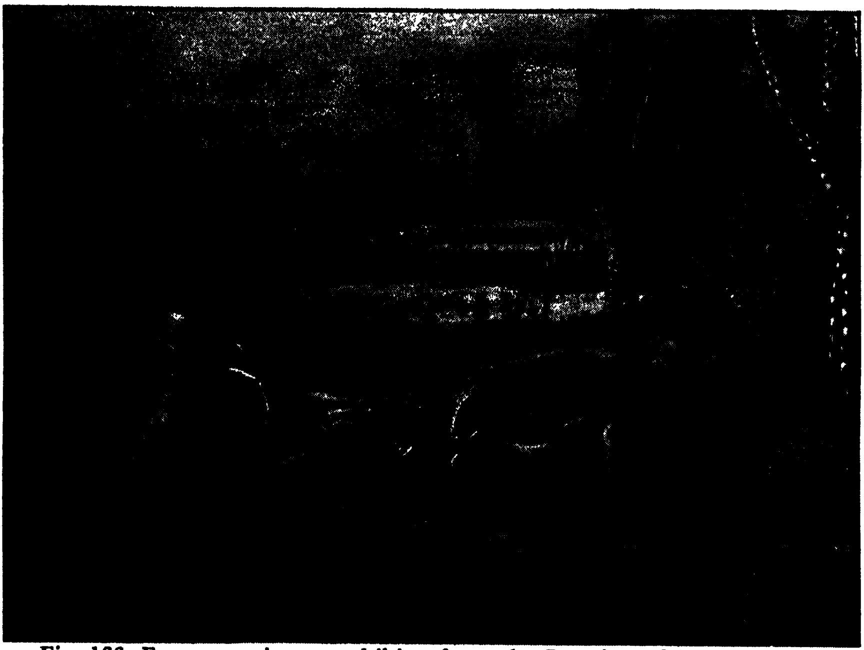

Fig. 166. Eryops, a giant amphibian from the Permian of Texas. *By John Jesse Hayes.*

The amphibians reached their climax in numbers and varieties during the widespread swampy conditions of the Pennsylvanian period, when tropical and subtropical conditions prevailed in latitudes far higher than at present. Some of the large fossil forms of the Permian and Triassic periods reached the great length of 10 feet. The amphibians have not been eminently successful either as aquatic animals or land-living forms, even though the group has been able to maintain itself against its enemies for many millions of years. The amphibians are reduced today to an inferior place among the vertebrates, and they will continue to decline and may eventually disappear from the earth. Their greatest handicaps lie in that they must always go back to the water during the egg-laying season and that they must constantly protect themselves against the dry air. One group, however, did give rise to the reptiles, and, because of this contribution to the evolution of life, they have probably justified the failures of other members of their race.

THE REPTILES

The amphibian ancestor of the reptiles solved a great evolutionary problem by evolving a new type of egg, which could be laid upon the land and from which the young reptile could emerge already adjusted to life on the land. The reptile egg is a great deal larger than that of the amphibian, and it is protected by a hard or leathery covering so that it does not dry up when laid upon the land surface. It also contains a great quantity of food to nourish the young animal until it reaches an advanced stage of development. Consequently, when the young reptile hatches, it is essentially the same as the adult except for the matter of size. There is no aquatic stage in its early life, so that gills are never needed. This release from the old aquatic environment that had so handicapped the amphibians was a very important forward step in the evolution of the vertebrates, because it meant that a group of animals had finally appeared that could begin to spread widely over the land and adjust themselves to the many varied types of environmental conditions available. The rise of the reptiles was slow at first, but eventually they became so numerous and developed so many different forms that they easily became the rulers of the land, the sea, and the air. This dominant position was maintained against all opposition for a hundred million years, and yet in the end most of the great groups disappeared from the face of the earth, leaving only a few modern forms.

Several forms that represent transition stages between the amphibia and the reptiles are very difficult to classify precisely because they have some of the characteristics of both groups. Such discoveries, however, are very valuable because they help demonstrate the concept of evolution.

The earliest reptiles walked with a sprawling posture, with their legs at right angles to the body. No animal with the limbs in this position could walk very well without taking numerous rest periods, and the body was in contact with the ground for long periods. Such a posture is seen among the lizards today. Although they are able to run rapidly for a short distance, the effort required to lift the body off the ground is tiring, and lizards are not great travelers. Turtles and crocodiles are other examples of living reptiles that have retained the old sprawling posture. The turtles have gone back to the water in many cases and their movements in the old aquatic environment is relatively easy. Other groups of reptiles became aquatic and semi-aquatic, this being the line of least resistance and a way of escaping from the difficulties of getting around on the land. In still other groups of reptiles the position of the legs shifted a little so that they were underneath the body; with this important change the reptiles began their real conquest of the land. Some reptiles abandoned the posture on all fours and learned to walk on their hind legs only. In such cases the front limbs were shortened and in some of the dinosaurs they became vestigial. The reptiles that returned to the sea became real "sea serpents" and in some cases their adaptation to the water was so complete that the legs were shortened or converted into paddles and the animals practically confined to the water. Some forms developed grasping hands and feet and may have lived in the trees, while others turned their arms into wings and took to the air. Flying reptiles were once world-wide in their distribution. The flying mechanism consisted of a greatly elongated fourth finger and a thin membrane of skin which was stretched from this long digit to the body.

Although the dinosaurs are extinct reptiles, this group alone was sufficient to have given the name, "Age of Reptiles," to the Mesozoic era. Dinosaurs spread over much of the earth's surface, and they must have been the dominant forms wherever they went. There were carnivorous, herbivorous, and omnivorous dinosaurs. Some lived entirely on the land and others led a semi-aquatic life. The largest of all the dinosaurs probably spent most of their lives in fresh-water lakes, rivers, and swamps.

THE BIRDS

The birds are so closely related to the reptiles that their only real distinguishing characteristic is the presence of feathers, and even these remarkable structures have evolved from the scales of the reptile. This close relationship to the reptilian stock is especially well shown in the earliest known representatives of the birds that lived in the Jurassic period. These feathered animals had well developed teeth in their jaws, functional fingers with claws on their wings, and a long bony tail like that of some of the small carnivorous dinosaurs. The only two known skeletons of these Jurassic birds were found in the Solenhofen lithographic limestone in Bavaria, and if the impressions of the wing and tail feathers had not been found with the bones, it would have been practically impossible to determine whether the creatures were birds or reptiles. The modern birds have lost their teeth and the long bony tail, but there still are vestiges of three fingers on the wings.

The strong flight feathers on the wings grow out of the flesh along

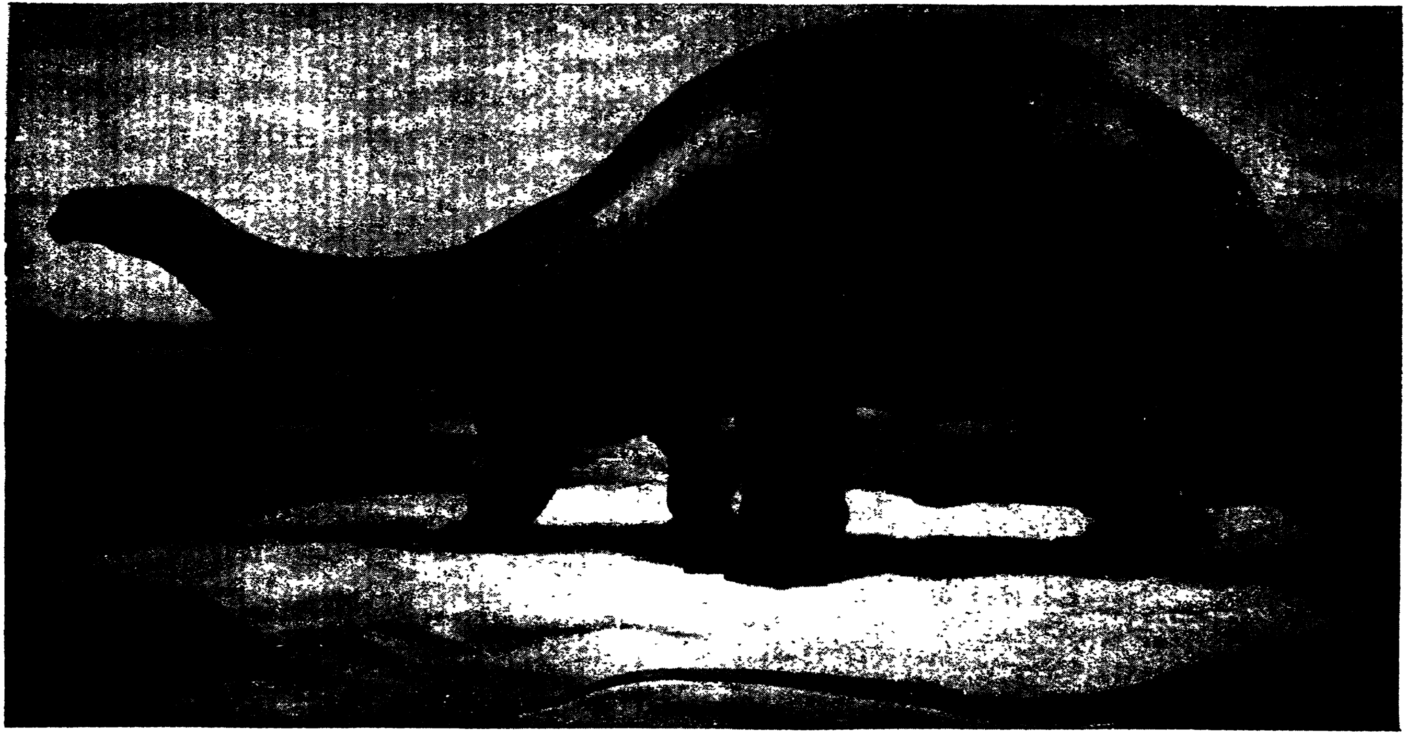

Fig. 167. A scene in the western United States during the Jurassic period. The great Brontosaurus shown may not have been able to walk freely on land, as shown here. His bulk may have been too great. *From a painting by C. R. Knight, courtesy Chicago Natural History Museum.*

Fig. 168. Plesiosaurs, marine reptiles in a Mesozoic sea. *By John Jesse Hayes.*

the back side of the forearm, while the rest of the body is covered with softer feathers which serve to insulate the body and maintain the condition of warm blood. The great bodily activity of the birds has made warm blood inevitable, and in this respect they differ from the reptiles, although something approaching the warm-blooded condition may have been characteristic of some of the more active reptilian forms.

Birds still have scales on the lower parts of their legs, and the toes are equipped with efficient claws. The beginnings of teeth have been observed in some birds before they were hatched, but the development is never completed. The Hoatzin is a peculiar bird that lives in the tropical parts of South America and it has functional claws on the first and second fingers of the wings. These claws are used for climbing around through the trees and are reminiscent of the climbing habits of the Jurassic birds, *Archaeopteryx* and *Archaeornis,* which had three functional claws on their fingers.

The wings of the Jurassic birds were weak, and the small size of the breastbone would further indicate that their powers of flight were not developed much beyond the gliding stage. Some authors derive the birds from a small arboreal reptile, while others believe that they evolved from an active land-living reptile. Some of the small carnivorous dinosaurs have skeletons that are quite similar to those of Archeopteryx and Archaeornis.

The Cretaceous bird called *Ichthyornis* had well developed wings, and teeth were still present. Toothless birds appeared towards the end of the Mesozoic era, and the modern types have had their great radiation since the beginning of the Tertiary period. Several types of giant, flightless birds appeared during the Cenozoic era; their remains have been found in North and South America, New Zealand, and Madagascar. Some of these birds reached a height of 10 feet, and the great moas were still living in New Zealand when the islands were invaded by those bold navigators, the Maoris. Large flightless birds, the ostriches, are found today in Africa and closely related forms, the emus, are living in Australia. The dodo, a relative of the pigeon, lived on the island of Mauritius where it was finally exterminated by sailors in search of water and food. The passenger pigeon became extinct only a few years ago. The wings of the modern penguins are useless for flying, but, modified into paddles, they have made these birds powerful swimmers and divers.

The seasonal migrations of modern birds, among their most remarkable habits, are very difficult to explain. The migrations may cover several thousand miles, and they sometimes occur over great stretches of open water. Whatever the explanations may be, the phenomenon is usually witnessed twice a year, in the spring and in the fall. Birds are still very numerous, but they would be still more abundant if man, with his predatory habits, had not destroyed or occupied many of their nesting places. Some modern birds furnish man with a great deal of food, while others, by eating harmful insects, are a great help to farmers and orchardists.

THE MAMMALS

The mammals represent the highest group of vertebrates that has yet appeared, but the first fossil members of this great family are from rocks of the Jurassic age, which witnessed the climax of many orders of reptiles also. The reptilian stock which gave rise to the mammals has been traced back to the Permian period, and the mammal-like reptiles from the Permian and Triassic of South Africa are very close to the main line of evolution which culminated in the true mammals. The mammalian characteristics of these reptiles are shown in many parts of the skeleton. The legs have moved into the positions in which they are found in the typical four-footed mammals, the tooth-bearing bone in each half of the lower jaw is very prominent, and the skull has as many mammalian as it does reptilian characteristics. It is impossible to say whether these animals had evolved the warm-blooded condition that is characteristic of all the mammals, but they had doubtless made some progress, at least, in that direction. The body covering is also unknown, but some ancestral form must have developed hair which is still found in nearly all mammals. The four-chambered heart is associated with warm-blooded animals and is found in the birds and mammals.

The brain is much better developed among the mamals than in any other vertebrate group, and this feature, together with the more highly developed nervous system, is responsible for the alertness and activity that are characteristic of the mammals.

The teeth of the mammals are differentiated into incisors, canines, premolars, and molars, and the common number of teeth among the early members of the group was forty-four. Most modern forms have fewer than this number.

The modern duckbill, or platypus, and the spiny anteater, both of the Australian area, are strange creatures. They are mammals, but instead of bearing their young alive, they lay eggs after the manner of reptiles. These strange creatures are "living fossils," or hold-overs from the age of reptiles when the ancestors of the mammals were changing from the egg-laying method of reproduction to that of the modern placental type in which the young are born alive.

The marsupials, or pouched mammals, represent another primitive type. The young marsupials are born in such an immature stage of development that they must be sheltered in a special pouch on the abdominal surface of the mother. Here they remain and are nourished by milk until they are able to take care of themselves. The opossum is the only marsupial that is living in North America, but many fossil forms have been found. The egg-laying mammals and considerable numbers of marsupials, such as the kangaroo and the wallaby, are still living in Australia because that great land mass was separated from the mainland of Asia before the fierce and predatory placental mammals were able to reach the Australian region.

The flesh-eating mammals have highly specialized teeth that are useful in capturing, holding, and tearing their prey. The incisor teeth are for biting or nipping, and the long canines are capable of tearing flesh and inflicting terrible wounds by stabbing. The scissor-like teeth on the sides of the jaws are highly specialized for slicing and cutting. These teeth are long, with a narrow upper surface, and when in use the teeth in the lower jaws move along the inside of those in the upper jaws, thus making efficient shearing devices. The majority of flesh eaters must capture their own food and consequently have developed the two valuable characteristics of speed and cunning. They are usually able to outwit the herbivorous mammals. Cats, weasels, and dogs are typical carnivores.

There are semi-aquatic mammals like the hippopotamus, otter, beaver, muskrat, seal, and sea lion; and other forms, like the whale and porpoise, live entirely in the water. The polar bear is an example of a modern mammal that is in process of adapting itself to a semi-aquatic life. This bear is a powerful swimmer and is very much at home in the water. The bottoms of the broad, flat feet are covered with hair. The polar bear eats seals and fish during the long winters and in the short summers its food consists partly of berries and even grass. Prairie dogs, coyotes, and jack rabbits are able to live in semi-arid regions, and the Arctic wolf endures the severe cold of the northern regions. The bats have modified their arms into wings and are the only known flying mammals. The presence of sharp claws enables some forms to climb, and some groups, the monkeys, for instance, spend most of their lives in the trees. The elephants are the largest land mammals living today. Some mammals, such as cattle, sheep, and pigs, have been an extremely important source of food for many races of human beings for several thousand years, and the loss of this concentrated energy-producing food would be a serious matter for mankind. During the latter part of the Pleistocene, or Ice Age, thousands of wild horses were killed and eaten by men of the Old Stone Age. For many centuries the Eskimos have depended upon the skins of mammals for clothing and upon their flesh for food.

The anteaters of South America have a specialized diet that consists almost entirely of insects. The mouth is a very small opening at the outer ends of the jaws, through which a long, sticky tongue is thrust into a nest of insects, which are drawn into the mouth. The tree sloths live in the forests of South America and spend most of their lives hanging from the undersides of branches by means of their long, curved claws. Their movements through the trees are

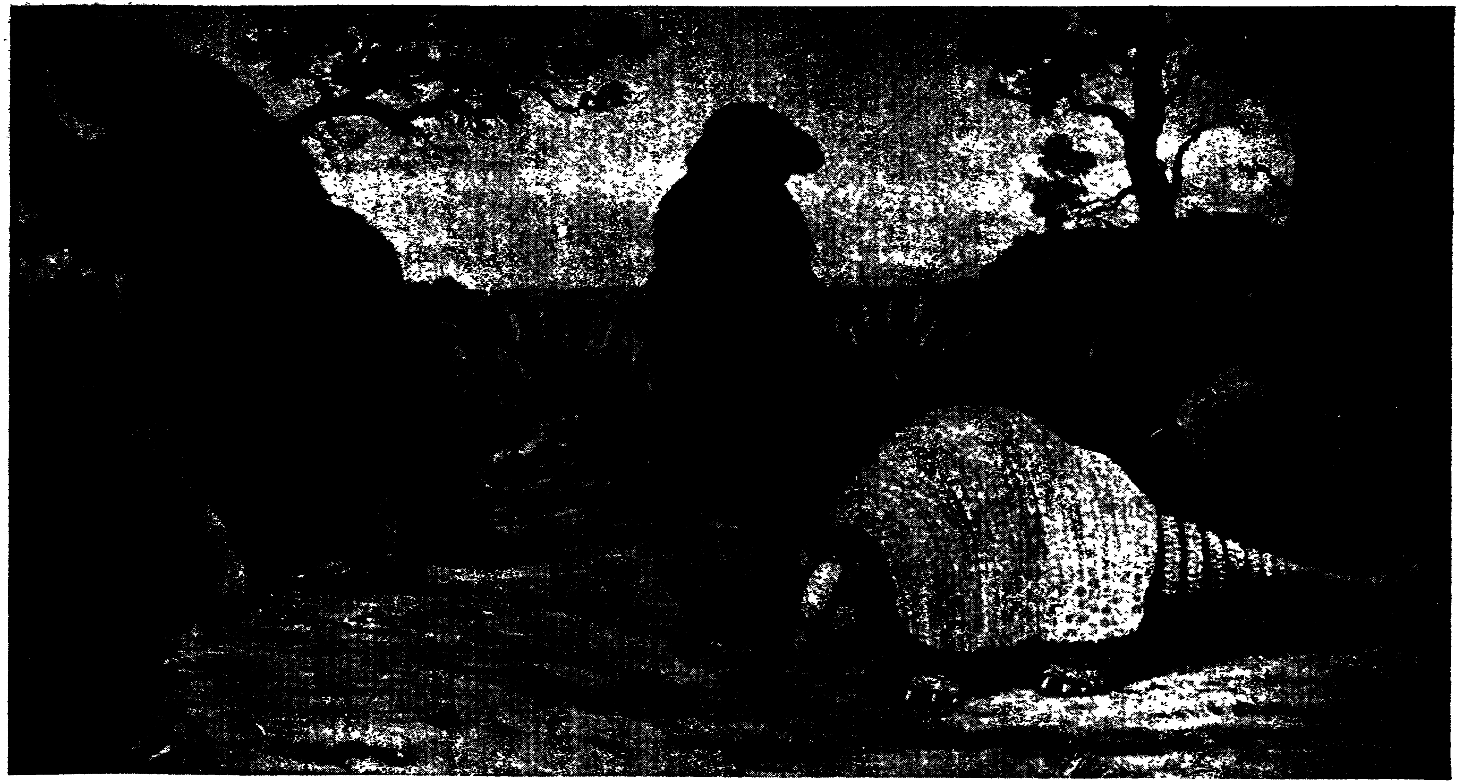

Fig. 169. The great ground sloth (left) and giant armadillo-like glyptodont (right) of the Pleistocene of western North America. *From a painting by C. R. Knight, courtesy Chicago Natural History Museum.*

slow and laborious, and they are especially helpless upon the ground.

Primates. The primates, another branch of the mammal group, include the lemurs, monkeys, great apes, and men. Since fossil primates are rare, the geologic history of this group is imperfectly known, but they appeared in the early Tertiary and spread to all parts of the world. The primitive North American forms disappeared after the Eocene epoch, but certain species have continued to live in Central and South America until the present. The primates specialize in size and quality of brain, and the later forms, that eventually evolved into man, became very skillful with their hands and developed a great variety of tools and implements. This tool-making and tool-using ability has reached an extarordinary stage of development among some of the modern races of men.

The lemurs live today in the forests of tropical Asia and Africa, but they are most abundant on the island of Madagascar, where they live isolated from their natural enemies, the predatory mammals. Monkeys are higher types of primates than the lemurs, and they are found in both the Old World and the New World. The South American monkeys have widely separated nasal openings, and they have evolved into a great many different varieties. Some of the Old World monkeys spend much of their time on the ground, where they walk on the palms of the hands and the soles of the feet. The barbary ape, which lives on the rock of Gibralter, is the only European monkey.

The great apes. The manlike apes include the modern gibbon, orangutan, chimpanzee, and gorilla. These animals are structurally close to man, but they are not in the direct line of descent to the modern races of human beings. The small gibbon is largely arboreal, while the huge gorilla spends most of its time on the ground, where it commonly walks on all fours.

CHAPTER 16

The Geologic Story of the Earth

THE EARLY PARTS OF THE EARTH'S HISTORY, for an unknown time after it became a planet, cannot be read; but when the solid crust was formed, and especially with the sedimentary rocks, the writing of an amazing history began. The record is found in all the rocks that make up the crust of the earth, but not all of the record is accessible because so many of the older rock formations are covered up by later deposits. Erosion has removed thousands of feet of rocks from all the continents, and there is no geologic period that has not lost some important part of its once recorded history because of the destructive effects of weathering and erosion.

THE ARCHEOZOIC ERA

The oldest known rocks belong to the Archeozoic era, and the base of this great system has never been seen, from which facts we may infer the presence of even older formations. The record of this first era is a difficult one to read, because most of the rocks are buried beneath younger formations, and even those rocks that are exposed have been greatly altered by metamorphism. In some cases, the original nature of the rock cannot even be determined.

There is a good exposure of Archeozoic rocks in walls of the Grand Canyon of the Colorado River, in northwestern Arizona, where the Vishnu series may be seen for several miles along the river at the very bottom of the great gorge. The rocks consist of schists, some of which were doubtless originally sediments, together with great intrusions of igneous rocks in the form of dikes. The total thickness of the whole series is unknown, because the bottom is not exposed, but it is several thousand feet deep, at least. After the deposition of the Vishnu series, these rocks were subjected to great mountain-making forces which upheaved a range of mountains that extended north and south from the Grand Canyon region for unknown distances. The evidence for the former existence of this mountain range is found in the rocks themselves. The alteration of the original formations into schist requires the tremendous forces of regional metamorphism, which are developed during the upheaval of mountains.

The old expression "everlasting hills" is not a very accurate one, as geologists measure time, because, no matter how lofty a mountain range may be, it will gradually disappear under the slow but inevitable action of the various weathering agents. The Grand Canyon Archeozoic mountains were slowly reduced to a peneplain, and this ancient erosion surface may still be traced for several miles along the walls of the canyon. Geologists have no accurate method of determining the height of the ridges and peaks in an old range of mountains that have been worn down to the mere stumps, but in a few cases the approximate width and length of the original mountain area can be determined, and from these the former height may be estimated.

The Lake Superior region of the United States and extensive areas north and northeast of the Great Lakes in Canada were affected by

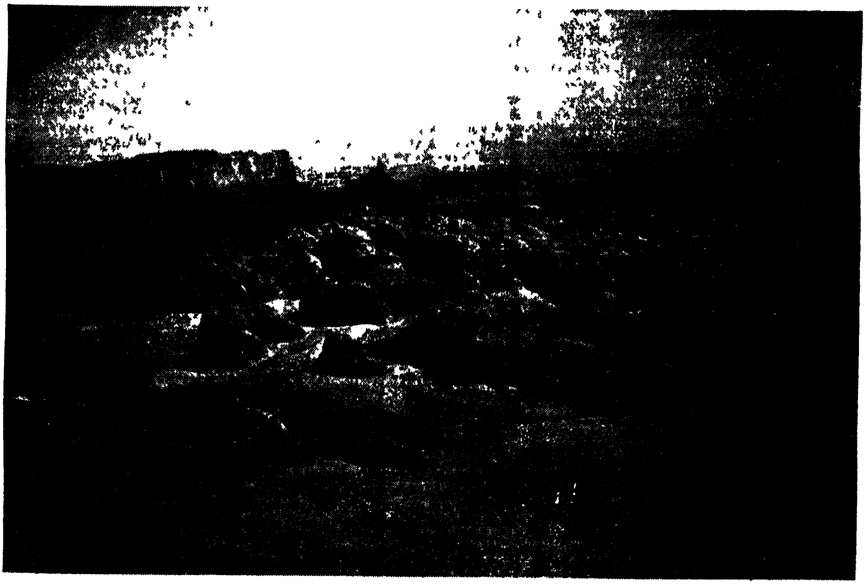

Fig. 170. Monument Valley in southern Utah—the remnants of an ancient peneplain. *By permission Spence Air Photos.*

two great periods of mountain building. The first one, called the Laurentian Revolution, came about the middle of the Archeozoic, and the second one, the Algoman Revolution, occurred at the end of the era. Both of these far-flung revolutions were accompanied by great intrusions of granite batholiths, and, as the mountains were gradually worn down, these once deep-seated intrusive masses were exposed and may be seen today in several places north and east of the Great Lakes. The present surface of Canada, except for the mountainous parts in the east and west, has been reduced to a relatively flat area called the Laurentian peneplain or the Canadian Shield.

The Grenville Series. The Grenville series of rocks outcrops from the Adirondack Mountains of upper New York northward for more than a hundred miles into Canada, and this series is especially important because it contains important indirect evidence of some kind of life that lived during the Archeozoic. A considerable part of the Grenville was originally limestone, and it may have been formed, at least in part, by plants and animals. These calcareous portions contain the famous *Eozoön canadense* which consists of serpentine and calcite in alternate light green and gray bands. It was formerly believed that these hemispherical masses of *Eozoön* were made by algae, but they may be entirely of inorganic origin. However, the Grenville also contains enormous quantities of carbonaceous material in the form of graphite, and it seems likely that this material was formed by plants, and possibly animals, that lived in the Grenville sea. No unquestioned fossils have ever been found in Archeozoic rocks, and there are several possible reasons for this absence of fossilized organisms. It is true that the earliest forms of life were without hard parts and so could not have been preserved as fossils. Most of the Archeozoic sediments, including those of the Grenville, have been metamorphosed, and any organisms that might have existed in the ancient waters were probably destroyed long ago.

Archeozoic ore deposits. The iron ore that is found in the Vermilion range of Minnesota is probably of Archeozoic age, although some geologists believe it was deposited in the Proterozoic era. The fabulous gold deposits of the Kirkland Lake and Porcupine districts of Canada are of Archeozoic age. An important deposit of pitchblende, which has recently assumed world-wide significance because of the development of atomic energy, occurs in Archeozoic rocks near Great Bear Lake in the Canadian Northwest.

THE PROTEROZOIC ERA

The widespread igneous activity of the Archeozoic era gradually became less intense, and the rocks of the Proterozoic era are dominantly of sedimentary origin. Many of the formations are not metamorphosed. Proterozoic rocks are exposed in the walls of the Grand Canyon of the Colorado, and in Glacier National Park of Montana, where the formations are 10,000 feet thick.

Continental glaciation. Periods of continental glaciation have occurred at long intervals in geologic history; the first recorded one is from the Proterozoic rocks of southern Canada and the northern United States. The original extent of the glacier is unknown because only remnants of the tillite remain.

Mineral deposits. The vast iron ore deposits of the Lake Superior region were formed in the Proterozoic era, and the great open pit mines of the Mesabi range in Minnesota are among the wonders of the world. Important mines are also operating in the Marquette-Crystal Falls districts of Michigan. Much of the high-grade ore in the Lake Superior district has been mined, but there are still great quantities of lower-grade ore. The amazing recent industrial development of the United States has been in large part controlled by the richness of the Lake Superior ore, its accessibility, and the fact that it can be shipped cheaply by boats operating on the Great Lakes.

The rich native copper deposits in the western part of the Northern Peninsula of Michigan were discovered centuries ago by Indians who operated several shallow mines in the Copper Country, and the later exploitation of the great Michigan copper ore bodies has given us some of the most fascinating chapters in the whole history of American mining. Some of the mine shafts reach a depth of about two miles down the dip. Many of the once great mines are now closed because the expense of mining copper at such great depths is so great that Michigan copper can no longer compete with that of other districts.

Most of the nickel that is used today comes from mines that have been opened in Proterozoic rocks in the Sudbury district of Ontario, Canada.

The Killarney Mountains. A tourist in the Northern Peninsula of Michigan, when he approaches the city of Marquette from the east, will see in the distance a range of low hills stretching northeast and southwest of the city. There is nothing very impressive about the height of these hills today, and yet they are all that is left of the once rugged Killarney Mountains. These mountains have been traced for about 700 miles from Ontario, through the western part of the Northern Peninsula of Michigan, and into Wisconsin. Their former extent toward the southwest must have been much greater, but the hills disappear in that direction beneath a cover of Paleozoic sediments.

Life of the Proterozoic Era. Fossils are very rare in Proterozoic rocks, and yet a few have been found, proving that both plants and invertebrates were in existence. Great colonies of calcareous algae occur in the Grand Canyon region and in Glacier National Park. A few thin-shelled brachiopods and some sponge spicules have been discovered, but the list is not very impressive.

THE PALEOZOIC ERA

The Cambrian Period. Geologic history becomes much clearer with the opening of the Paleozoic era, largely because of the numerous fossils, both invertebrates and vertebrates, that the sedimentary rocks contain. Each period in the Paleozoic era witnessed the invasion of the continents by shallow bodies of marine water called epeiric seas, which were temporary when compared with the oceans and changed their outlines frequently during each period. Relatively slight elevations or depressions of the continents, in various places, definitely cause extensive changes in the positions of the shore line. The average depth of these seas was probably less than 200 feet, but during the Paleozoic and Mesozoic eras they received great quantities of marine sediments, which today contain an important record of the marine life of those times.

Geosynclines are long and relatively narrow, trough-like areas, bordered on at least one side by a high land or by a land that rose intermittently during a great interval of time. Sediments from the land were carried by streams and deposited in the sea that covered the area of the geosyncline, and, as the deposition continued, the bottom of the trough subsided until sediments to a thickness of many thousands of feet had accumulated in water that was always shallow. Pressure applied to these thick sedimentary accumulations resulted in the upheaval of extensive mountain ranges in nearby areas. Most of the great mountains of the past and the present were formed in this manner.

The Appalachian geosyncline originally occupied the approximate position of the Appalachian Mountains, and it was bordered on the east by the Land of Appalachia which stood at its highest elevation in the Cambrian period and was gradually reduced during later periods. The Cordilleran trough was located about where the modern Rocky Mountains of Canada and the United States are found, and it was bordered on the west by the Land of Cascadia. The interior of North America stood at a comparatively low elevation during the Paleozoic era, and the areas both of the geosynclines and of the interior of the continent were frequently invaded by epeiric seas.

A typical cycle of marine invasion began in the early Cambrian period when epeiric seas invaded the Appalachian and Cordilleran geosynclines from the north and south ends. The invasion continued until both troughs were filled with marine water, and, at about the middle of the period, the sea began to move eastward from the Cordilleran trough across the northern part of the United States. At the climax of the inundation there may have been a continuous waterway from the east to the west. Waters also invaded the Ouachita geosyncline, which extended east-northeast across northern Mexico, Texas, and Oklahoma, and the sea in this trough finally merged with the one that extended eastward from the Cordilleran geosyncline. Finally, towards the end of the Cambrian era there was a general rise of the North American continent; the epeiric seas gradually withdrew until the land was completely above the ocean level. Similar invasions and retreats occurred in the other periods of the Paleozoic era, but the marine water did not cover exactly the same areas that had been covered during the Cambrian. The numerous fluctuations of these epeiric seas during each period make it impossible to determine just how much of the continent was under water at any one time.

As the epeiric seas invaded the land, marine organisms that had been living in the oceans came in with the advancing water and occupied extensive areas on the sea bottoms, or floated freely at the surface, according to their various habits of life. Many of these animals, with hard shells and skeletons, sank after death to the sea bottom, where they were buried in the accumulating sediments.

Some extremely fine exposures of Cambrian rocks are found in the mountains of British Columbia, while others of a less picturesque nature occur in the Rocky Mountains of the United States, in the upper part of the Mississippi Valley region, and in the Appalachian Mountains. The famous Ausable Chasm, in the Adirondack region of New York, has been eroded out of the Potsdam sandstone of Upper Cambrian age.

Life of the Cambrian. By the beginning of the Cambrian many of the modern phyla were already in existence, but Cambrian rocks contain the first abundant fossils. This fact points to undiscovered ancestors that must have lived in Pre-Cambrian times. Trilobites, who had already reached a high stage of development, dominated the Cambrian seas. The remarkable fauna from the Burgess shale near Field, in British Columbia, contains a great many soft-bodied animals that are preserved in remarkable detail.

The Ordovician Period. The marine cycles of the Ordovician period include the great Richmond sea, which covered, in its various pulsations, about half of North America. Richmond rocks, wherever they are found, contain a very rich and characteristic fauna. Southeastern Indiana, southwestern Ohio, and the Northern Peninsula of Michigan are famous collecting grounds for Ordovician fossils.

Life of the Ordovician. The floating marine animals called graptolites were abundant during the Ordovician period, and their remains are usually found preserved in dark colored shales. Cup corals were very common, and compound corals were locally abundant. Many genera and species of brachiopods lived in the Ordovician seas and some of them preferred slightly muddy sea bottoms. There were numerous representatives of the fragile crystoids, but their remains are rare. The first starfish appeared in the Ordovician period. Cephalopods with long, straight, megaphone-shaped shells were especially abundant, and some of their shells reached a length of over ten feet. Trilobites were still common, and some individuals were 18 inches long.

The first vertebrates. Fossil remains of vertebrates appear for the first time in Middle Ordovician rocks. Their discovery was made at Cañon City, Colorado, but they have since been found in the Black Hills, the Big Horn Mountains, and in the Northern Peninsula of Michigan. The remains consist of plates and scales that formed the dermal armor of primitive types of fishes called Ostracoderms. A portion of a jaw set with teeth has been found in the lower Ordovician rocks of southeastern Missouri, and it has been proved to have belonged to a primitive form of fish. The appearance of vertebrates is an event of the greatest significance, because they represent some of the earliest members of a group that became increasingly important during geologic time and finally dominated the entire earth. When man, the great predatory vertebrate, appeared, he set out upon a course of destruction that has led to the extermination or near-extinction of many other members of the group.

The Taconic disturbance, which occurred toward the close of the Ordovician period, resulted in the upheaval of a mountain range that extended from a position at least as far north as Vermont, southward through eastern New York and Pennsylvania to Virginia. The present Green Mountains of Vermont are the re-elevated stumps of the ancient Taconic range.

Economic deposits. The Trenton dolomite in the Ohio-Indiana oil field has produced petroleum and natural gas since 1883. Maximum production was reached in 1896, and the field is now almost abandoned. If the gas pressure had not been exhausted so rapidly in the early days of production, the field might have had a much longer life. Ordovician formations, including both dolomites and sandstones, have become of great importance as sources of oil and gas in parts of Kansas, Oklahoma, and Texas.

Ordovician limestones in various parts of the Appalachian region, especially in Vermont and Tennessee, were metamorphosed during the Taconic disturbance into high-grade marble, used extensively where highly polished stones are needed in buildings. Ordovician limestone and dolomite are crushed and used in building roads and as a flux in the smelting of iron ore. Pulverized limestone is spread over farm lands where the lime content of the soil is low. Ordovician muds, which came largely from the Land of Appalachia, have been altered into slate, used for roofing purposes. Lime phosphate, a valuable fertilizer which came from small Ordovician snail shells, is found in Tennessee. The St. Peter sandstone is composed of pure quartz grains and is used in making glass for windows and for optical purposes. Important deposits of iron ore are found in Ordovician rocks in Newfoundland.

The Silurian Period. Climatic conditions in the geologic past are difficult to determine in detail, but there is evidence that well defined zones of climate, like those of the present, have not always existed. Instead, the evidence indicates that climates of the past have been more uniform over large areas of the earth than are those of the present. The proof of this greater uniformity is found in the widespread distribution of similar forms of plants and animals from the subtropics to the north polar regions. Reef-building corals are particularly valuable as barometers of past climates because they have always lived in marine waters whose temperature cannot be colder than about 68 Fahrenheit degrees. Typical reef-building corals are found widely distributed throughout rocks of the great Middle Silurian or Niagaran sea. They have been found in Greenland and the Arctic regions of North America, and numerous reefs or bioherms, containing many types of corals, occur in the northern part of Michigan, Wisconsin, Indiana, and Ohio. The corals are similar in these different areas, and they must have lived in a warm, shallow, sea.

Good exposures of Silurian rocks are found in the Niagara gorge and at the falls themselves, where the top rock is the Lockport dolomite. The soft shales below the hard Lockport are worn back rapidly by the force of the spray from the falls until eventually the cap rock becomes top-heavy and drops to the foot of the cliff, causing a recession of the falls. During the last 25,000 years Niagara gorge has been eroded headward a distance of about eight miles from the original fall zone—the Niagara escarpment at Lewiston, New York.

Economic products. During a part of late Silurian time, the region that is now the Southern Peninsula of Michigan, northern Ohio and Pennsylvania, western New York, and southwestern Ontario, was occupied by a partly cut-off arm of the sea. The climate was arid, and as the marine water evaporated, salt was precipitated in a series of basins. The supply of salt water was occasionally renewed through some channel that led in from the open ocean, and the bottoms of the various basins subsided until in some places the salt reached a thickness of more than a thousand feet. There is a great salt mine near Detroit, Michigan, and Silurian salt is obtained from brine wells in Michigan, Ontario, Ohio and New York.

Rocks of Middle Silurian age in the Appalachian region contain great quantities of low-grade iron ore. The chief mines are in the region of Birmingham, Alabama, where coal and limestone are also available, making possible the development of a great steel industry.

Life in the Silurian. A few fossil land plants have been found in Silurian rocks but they are not preserved in great abundance. Land plants become increasingly important in succeeding periods. Scorpion-like invertebrates, which probably breathed air and lived on the land, appeared in the Silurian.

The primitive fish called ostracoderms continued their development during the period, and some well-preserved remains have been found in Norway. The placoderms or fish with true jaws, were also present in this period.

The Devonian Period. When North America was a relatively low-lying land during the early part of the Devonian period, an epeiric sea invaded the Appalachian geosyncline. About the middle of the period another marine invasion began in the Alaskan-Mackenzie River area and spread southward over a wide region in the western part of North America into Mexico. A connection between the eastern and western seas was established across the northern and southern parts of the United States, and about 40 per cent of the continent was finally submerged.

The geologic record of the Devonian period in southern New York is unusually complete. The Oriskany sandstone was derived from crystalline rocks of the old Pre-Cambrian Adirondack dome of northeastern New York and the Land of Appalachia. This widespread deposit of sand was spread in the Appalachian trough from New York to Alabama. The Onondaga limestone was originally formed as an almost continuous deposit from Hudson Bay to Oklahoma and Tennessee. A reef composed of silicified Onondaga corals forms the "Falls of the Ohio River" near Louisville, Kentucky. This extensive limestone was followed by deposition of a black shale from New York and Pennsylvania westward to Kentucky, Ohio, Indiana, and Michigan.

The most significant events in the Devonian period are concerned with the evolution of land plants and air-breathing vertebrates. For several million years all the known plants had lived in the seas or fresh water. Their adaptation to the land was an event of the greatest significance, because without land plants as an ultimate source of food there could never have been a widespread evolution of land animals, either invertebrates or vertebrates. The few land plants that have been discovered in Silurian rocks give little clue to the amazing spread of plants widely over the Devonian lands. The first forests appeared at this time, and the fossil remains of these remarkable seed ferns have been found at several levels in Devonian rocks near Gilboa, New York, where the stumps are still in place, with their roots deploying through shale that was once the original soil. Not only are plants important for their food value, but they lend great beauty and interest to the landscape, which must have been relatively bare for millions of years before the Devonian period. We cannot assume that the Devonian land animals appreciated the trees for their aesthetic value, but without these primitive plants as the ancestors of later and more modern types, there never would have been any land vertebrates, and life would still be confined to the water.

Siliceous or "glass sponges" were very common in the Devonian period. These invertebrates are represented today by the "Venus Flower Basket." Reef-building corals were abundant in the warm, clear waters of the Onondaga sea. Brachiopods reached the peak of their development during this period, and enormous numbers of their perfectly preserved shells are found in some of the Devonian shales and limestones. Trilobites had passed the climax of their evolutionary development and were slowly declining.

Air-breathing vertebrates. The first known air-breathing vertebrates were the lung fishes of the Devonian period. These animals had evolved an air sac in the chest region and one of its important functions was that of a breathing organ. Modern fish have these swim-bladders, which enable the animals to remain in an upright

Fig. 171. Restoration of a Devonian sea bottom. *Photo by Richard Askew, Cranbrook Academy of Art.*

position, or to rise and sink in the water. The swim-bladder lungs of the Devonian fish were a little too close to the ventral side of the body to make them efficient for balancing purposes, and in the modern forms they have moved to a position slightly above the throat. The lungs of the Devonian fish enabled the animal to breathe air by thrusting its nose and mouth above water. Air-breathing fishes are still living in South America, Africa, and Australia, but in the Devonian period they were world-wide in their distribution. The modern Australian lung fish is a "living fossil" because it has descended from Devonian ancestors almost without change. The African air-breathing fish has been known to live for more than two years out of water.

The fishes that developed both lungs and leg-like fins probably made frequent excursions to nearby land in search of food, or possibly they were looking for another pool of water in case the old one started to dry up. These fish thus led amphibious lives and were probably the ancestors of the amphibians.

The earliest known amphibian remains are from Upper Devonian rocks of eastern Greenland and Quebec. Several skulls have been found from which it has been deduced that some of the animals were about four feet long. The presence of these large amphibians indicates that the climate of Greenland was much milder during late Devonian times than it is now.

The amphibians represent the first step in the adaptation of vertebrates to life on the land and to air-breathing habits. The reptiles carried this adaptation still farther, but they are cold-blooded animals and so are somewhat limited in their ability to live out-of-doors or on the exposed surface of the earth during cold weather. The warm-blooded birds and mammals, with their protective covering of feathers or hair, are able to live in hot or cold regions and have literally conquered the earth.

Age of fishes. The Devonian period is sometimes called the Age of Fishes, for fishes dominated the seas and land waters of that time. Fishes were numerous, and some of them reached the great length of more than 20 feet. Several groups developed heavy armor plate over the forward parts of the body. There were also primitive members of the shark family with skeletons made of cartilage like their modern descendants. The carbonized skin of the Devonian shark, Cladoselache, has been preserved in a number of specimens found near Cleveland, Ohio.

The Acadian disturbance. The observed effects of this mountain-making disturbance extend from the Acadian region of Canada southward through New Hampshire and along the western border of Appalachia Land to South Carolina. These mountains probably extended north of the Land of Acadia, but their exact coverage is not known. The present White Mountains of New Hampshire are the worn down remnants of a portion of the ancient Acadians. The modern Catskill Mountains of eastern New York have been formed by the dissection of a great mass of sedimentary material, mostly shale and sandstone, that was derived from the Taconic and Acadian Mountains.

Economic products. The famous oil district of western Pennsylvania has been producing oil from Devonian rocks since its discovery in 1859. The major oil-producing formations in the Southern Peninsula of Michigan are of Devonian age. The Oriskany sandstone is used in the glass-making industry.

The Mississippian Period. The Mississippian period was a time of comparative quiet and stability. A single great sea filled the Cordilleran geosyncline, and extended eastward across the Mississippi Valley region to the Appalachian trough. This was a time of extensive limestone deposition. The Indiana limestone, or Bedford oölite, is the most widely used building stone of today, and most of the supply comes from the quarries around Bedford, Indiana. The stone is thick-bedded and of very uniform texture. Blocks of almost any desired size are easily obtained.

The many hundreds of miles of caves in Kentucky have all been formed by solution of highly soluble Mississippian limestones.

Life of the Mississippian Period. The crinoids, or stone lilies, and the bud-like blastoids reached their climax in numbers and varieties in this period. Mississippian rocks have yielded the remains of about 300 different species of sharks, the majority of which had "pavement" types of teeth indicating that they fed largely upon mollusks and crustaceans whose shells were easily crushed by the specialized teeth.

The amphibians were consolidating their position as the highest group of vertebrates that had yet evolved, pointing towards a grand climax in the next period.

The Pennsylvanian Period and the formation of coal. The Pennsylvanian, the great coal-forming period of the Paleozoic era is sometimes called the Upper Carboniferous. Vast areas in the eastern half of the United States stood close to sea level during a part of the Pennsylvanian period, and extensive fresh water swamps formed over the great undrained areas. In the tropical climate, plants grew in great luxuriance both on the land and in the water. A great deal of this plant material fell into the swamps, where it slowly decomposed, and more was constantly added to the accumulating mass because the plants grew the year round. As the plants decomposed, some of their volatile constituents were lost, and lignite or brown coal was formed. Still later, sands, muds, and even limestones were deposited over the lignite, subjecting it to considerable pressure and driving off more of the volatile parts until soft or bituminous coal was formed. Anthracite or hard coal is a product of metamorphism, and the hard coal of eastern Pennsylvania is partly the result of the great pressures which were applied to the soft coal during the upheaval of the Appalachian Mountains at the end of the Permian period. Time was also an important factor in the whole process.

Some interesting alternations of marine and continental deposits have been found in a number of coal fields in the interior region of the United States. A bed of coal is covered by marine shale and limestone, then comes more coal, again followed by marine deposits. This cycle is repeated several times in some of the coal fields, demonstrating numerous fluctuations of the land and sea. A slight depression of the already low-lying land permitted a short-lived invasion of marine water which must have killed off the coal-forming vegetation. Then a slight rise of the land caused the sea to retreat, and coal forming conditions were once more established.

Not only is coal the most widely used fuel, but an amazing number of materials and articles are made in part from its constituents. Pennsylvanian rocks produce oil in the great Mid-Continent region of Texas, Oklahoma, and Kansas.

Life of the Pennsylvanian Period. The luxuriant growth of plants in the Pennsylvanian period was made possible by an abundance of rainfall and the warm tropical and sub-tropical climate which extended far into the Canadian region. The scouring rushes or Calamites reached the size of trees. Their modern descendants are common, but they are only three or four feet high, with the diameter of a lead pencil. The scale trees, Lepidodendron and Sigillaria, were gigantic in size. Some of them were more than a hundred feet in height with a diameter of six feet. Spindle-shaped Foraminifera, called "Fusulinids," were important rock-building protozoans in the Pennsylvanian.

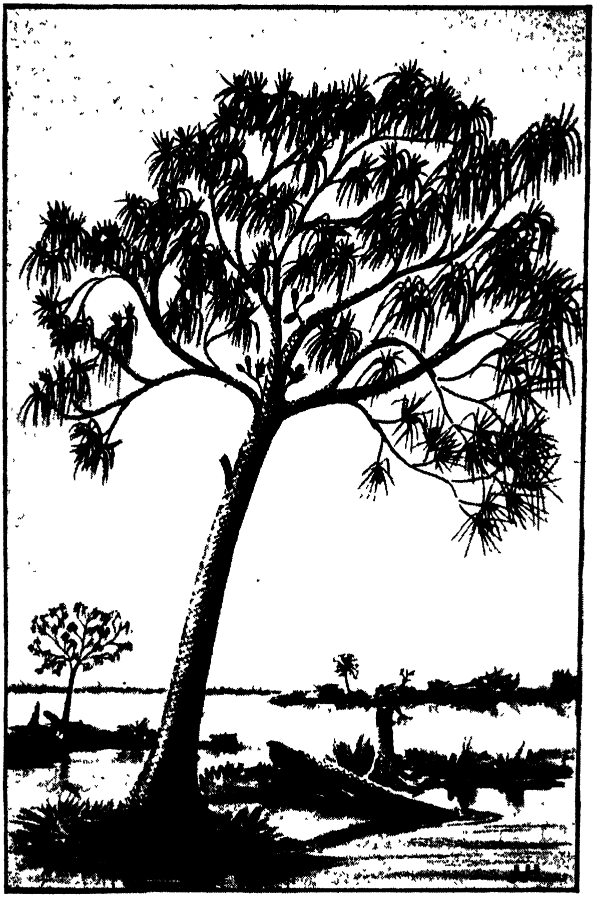

Fig. 172. Lepidodendron, a Pennsylvanian period scale tree. *By John Jesse Hayes.*

Insects probably originated as wingless forms as early as the Devonian period, but their fossil remains are exceedingly rare until the Pennsylvanian, when they suddenly appear in great numbers and many different varieties. Gigantic forms were very common. One dragon fly from the Coal Measures of Belgium has a wing spread of 29 inches. Large cockroaches were abundant, and spiders were present.

Amphibians. There was a great spread of amphibians through the rivers and fresh water swamps that covered such extensive areas in the Pennsylvanian period. Their evolution was greatly favored by the widespread mild climatic conditions, and the group reached its cli-

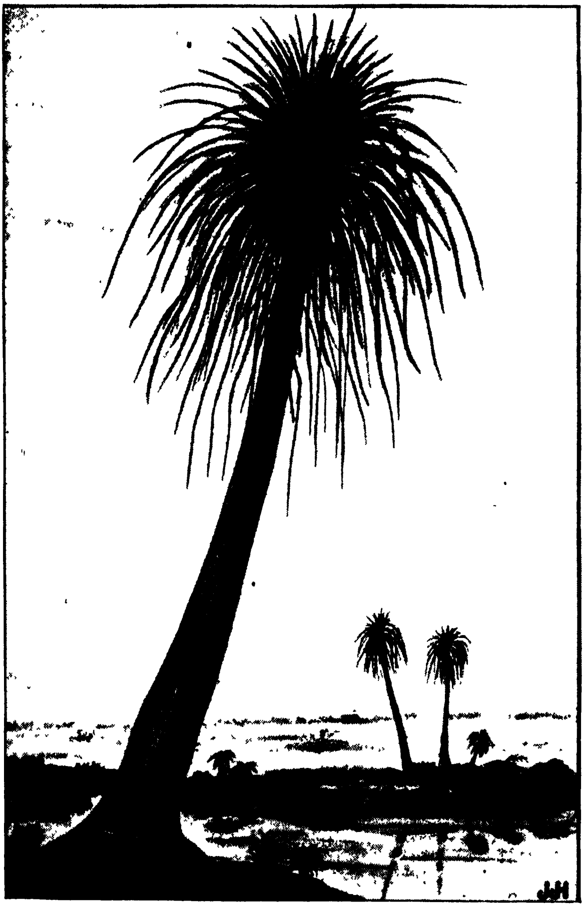

Fig. 173. Sigillaria, a scale tree from the coal-forming forest of the Pennsylvanian. *By John Jesse Hayes.*

max in genera and species at this time. Some of the Pennsylvanian amphibians were small like the modern salamanders and others reached the great length of 10 feet. One particularly large form from Kansas must have weighed several hundred pounds.

The first reptiles. The reptiles were the first vertebrates to lay their eggs on the land and free themselves completely from an aquatic life. Fossil reptiles are very rare in Pennsylvanian rocks, and their land-living habits are partly responsible for this scarcity.

The Permian Period. There was a comparatively small but general uplift of the central interior and eastern portions of North America towards the close of the Pennsylvanian period. The swamps disappeared, and the period of coal formation came to an end, while the climate in general became drier. The sea that covered a large area in the western half of the United States in the Pennsylvanian seems to have continued into the Permian with only minor changes in its position. The transition from the Pennsylvanian to the Permian is so gradual almost everywhere in the United States that it is impossible to fix a boundary between the sediments of the two periods. Marine water did not invade the Appalachian geosyncline area after the Pennsylvanian period; in the Permian the trough was a broad alluvial plain sloping gently westward.

The Dunkard Series. There is an interesting series of sediments, called the Dunkard, covering about 8,000 square miles in southeastern Ohio and adjoining parts of West Virginia and Pennsylvania. The rocks are mostly of continental origin, but some thin beds contain brachiopod shells of the primitive type called Lingula, as well as the spines of sharks. Their presence indicates that several temporary pulsations from the main Permian sea in the southwest reached eastward as far as southwestern Pennsylvania. The water at the eastern end of this embayment may have been brackish, but the fossils of a few marine animals that were able to live in the water have been found in the Dunkard sediments. The channel through which these temporary marine invasions reached their eastern terminus is not known.

Ancestral Rockies. Certain uplifted areas called the Ancestral Rockies, which rose intermittently in Colorado, New Mexico, and Texas during the Pennsylvanian and Permian periods, furnished most of the material that is found today in the great red beds of the western interior and southwestern portions of the United States. These deposits consist of muds, sands, and coarse gravels that were washed down from the Ancestral Rockies and deposited by intermittent streams that flowed with considerable volume only during the seasonal rains that came as cloudbursts do today. The red color was developed during the dry season by oxidation of the sediments. The fossil remains of amphibians and reptiles in the red beds mark the positions of ancient water holes or stream channels. The red beds are largely barren of fossils except for these scattered localities.

The red rocks in the Garden of the Gods, west of Colorado Springs, are of Pennsylvanian-Permian age. The great Carlsbad Caverns in the southeastern corner of New Mexico have been dissolved out of Permian limestone. The magnificent scenery of Monument Valley in northeastern Arizona has been carved largely out of red Permian sandstone. The Grand Canyon's rim rock is also of Permian age.

Continental glaciation. Extensive continental glaciers of Late Pennsylvanian and Permian age developed in South America, Africa, India, and Australia. Some of the glaciated areas are within the present tropics and sub-tropics, but the cause of this remarkable period of intensely cold climate is unknown.

Economic products. Permian rocks in southern Oklahoma, the Panhandle of Texas, Wyoming, and Kansas have produced considerable quantities of oil and gas. The Permian potash deposits of southeastern New Mexico and western Texas are of great value. Extensive deposits of salt and gypsum are found in the Permian rocks of Kansas, Oklahoma, Texas, and New Mexico.

The Appalachian Revolution. The Appalachian geosyncline began to receive sediments from the old borderland of Appalachia in the Cambrian period, and the deposition of land-derived material continued intermittently during most of the Paleozoic era. Some limestones and dolomites were also deposited in the subsiding trough, in addition to the muds and sands. The thickness of the sediments varies from about 10,000 feet in some parts of the trough to almost 40,000 feet in other parts; the average thickness is approximately 30,000 feet. Towards the end of the Permian period, tremendous pressure was brought to bear upon the eastern side of the Appalachian trough, and the sediments were upheaved into a range of mountains that corresponds roughly with the modern Appalachians. The direction from which the pressure came is determined by observing that most of the folds are slightly overturned toward the west, and the most intense folding and faulting are along the eastern side of the mountain belt. This first generation of Appalachian Mountains probably rose to great heights, but like all old ranges they were eventually reduced to a low, rolling plain. The modern Appalachians were formed at a later time.

Life of the Permian Period. The widespread distribution of a distinctive group of plants called the Glossopteris-Gangmopteris flora in South America, Antarctica, South Africa, India, and Australia suggests that these regions were once connected by land bridges across which the plants were able to migrate. Rocks of Lower Permian age near Elmo, Kansas, have yielded the well-preserved remains of more than 10,000 insects.

Amphibians were still numerous in those regions where permanent

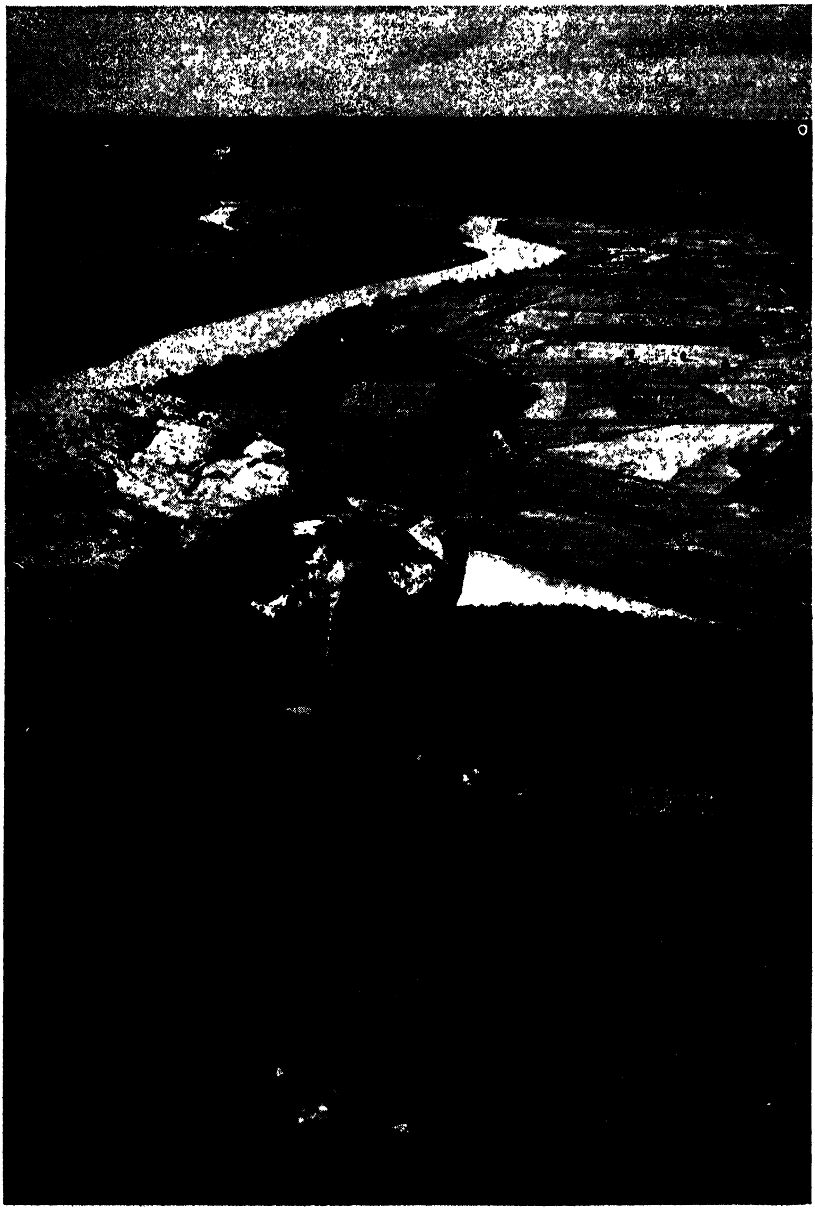

Fig. 174. View of the Schooley peneplain from Lookout Mountain on Moccasin Bend of the Tennessee River.

bodies of water existed. Reptiles were very abundant, and they began their long period of dominance at this time. The most important event in the evolution of life was the appearance of the mammal-like reptiles in South Africa. These animals were transition forms between the reptiles and the mammals.

THE MESOZOIC ERA

The Triassic Period. Broad continental uplifts had lifted the North American continent completely above the sea by the beginning of the Triassic. At no time during the period was North America invaded by an extensive epeiric sea.

The Newark group. This interesting and important group of rocks is all of continental origin, and the materials accumulated in a number of down-faulted troughs or grabens that extended in a broken series along the Atlantic coastal area from Nova Scotia to North Carolina. Lava occasionally flowed out over the floors of some of the grabens, and the sediments were intruded by a number of sills. Late in the Triassic period the rocks of the Newark series were strongly broken up by block faulting, and upturned edges of the tilted blocks formed the crest of the Palisade Mountains. The modern Connecticut Valley in the states of Massachusetts and Connecticut occupies the former position of one of these fault troughs.

Triassic of the Southwest. The Triassic rock in the southwestern part of the United States is notable for the presence of several vividly colored "painted deserts" and the famous petrified forest near Holbrook, Arizona. Thousands of petrified logs, ranging up to 10 feet in diameter and 120 feet long, are found in the whole forest area. These trees grew originally along the stream courses and wherever plenty of moisture was available. Many of those that grew near the river fell into the water and were carried downstream and buried either in the beds of the rivers themselves or on the valley flats along the stream courses during flood times. The logs were gradually covered by the accumulating river sediment and were petrified after the burial was completed.

Life of the Triassic Period. The invertebrate life of the seas was especially notable because of the presence of enormous numbers of highly specialized cephalopods called ammonites. The tightly coiled shells of these animals varied in diameter from a few inches to almost six feet, many of them ornamented with spines and ridges. Their variously colored shells must have presented a beautiful sight in the Triassic seas.

The reptiles were increasing in numbers, and some of them, such as the alligator-like phytosaurs, had become semi-aquatic in habit.

There were also true marine reptiles which represent some remarkable adaptations to life in the sea. Remains of ichthyosaurs 25 feet long have been found in California and Oregon. This group is discussed later. Plesiosaurs were also in existence. Triassic rocks in the Connecticut Valley have preserved great numbers of dinosaur footprints that were once thought to have been made by birds. A few incomplete skeletons of these animals have been found, representing several varieties. Most of the dinosaurs were small, although some were about 15 feet long. The mammal-like reptiles show some advance over the Permian forms and they are closer to the true mammals.

The Jurassic Period. No rocks of the Jurassic period have been recognized in the eastern part of the United States, prob ably because, since that part of the country stood at a high elevation above the sea, erosion was going on rapidly, and the products of the erosion were carried eastward into the ocean.

Ancient sand dunes. Some of the thickest and most extensive sand deposits that have ever accumulated were formed in southern Utah, north of the Grand Canyon region, during Jurassic time. The Wingate sandstone makes the Vermilion Cliffs, and the spectacular and beautiful Zion Canyon has been carved out of the Navajo sandstone. The vertical cliffs in this magnificent canyon rise to heights of a mile above the floor of the valley, and the colors are chiefly white and red. Rainbow Natural Bridge in southern Utah has also been formed from Jurassic sandstone.

The Sundance Sea moved southward from northwestern Canada into the Rocky Mountain geosyncline and reached northern Arizona and New Mexico. It was unusually shallow, and the deposits vary radically from place to place. Some of the sediments are the reworked materials that had accumulated on the arid floor of the Rocky Mountain geosyncline before the sea invaded the area.

The Morrison Formation. After the retreat of the Sundance Sea, a large area on the floor of the Rocky Mountain geosyncline, extending from Montana to New Mexico, was receiving the sediments of the famous continental Morrison formation. The region was well watered with numerous swamps, lakes, and rivers, in which the huge aquatic dinosaurs lived. Many other dinosaurs inhabited the Morrison area, as well as numbers of primitive mammals.

The Nevadian disturbance came towards the close of the Jurassic period, when mountains were upheaved along the western side of

North America, probably from Alaska to Mexico. Volcanic activity was intense at times during this great orogeny, and towards the close of the period of mountain building great batholiths were intruded into the base of the Nevadian range. The celebrated gold-bearing quartz veins, now exposed in the modern Sierra Nevada Mountains, were formed at this time.

Life of the Jurassic Period. The widespread distribution of a luxuriant warm-climate flora in the far northern regions shows that the

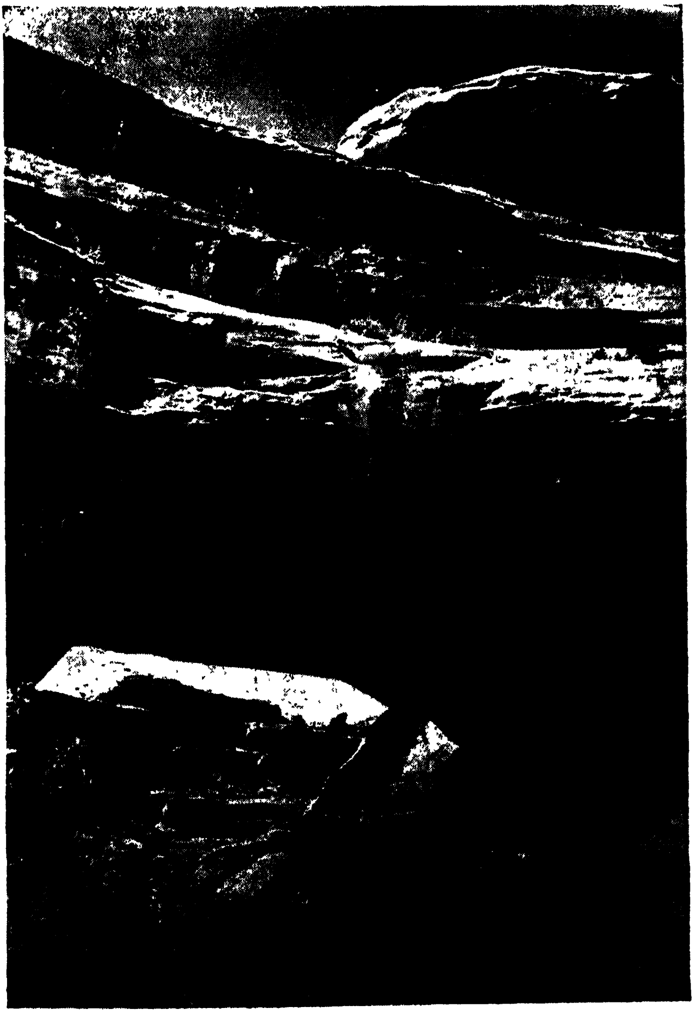

Fig. 175. Natural Bridge in San Juan County, southern Utah, formed in Permian sandstone. *By A. J. Eardley.*

Arctic had a much milder climate during the Jurassic period than it enjoys today. The palm-like trees known as cycads were especially common. They have been found in Jurassic rocks from Antarctica to Greenland and Alaska. The ginkgo tree was also widely distributed over the world. Today it is found chiefly in Japan and China.

The Belemnites, an ancient type of squid, lived everywhere

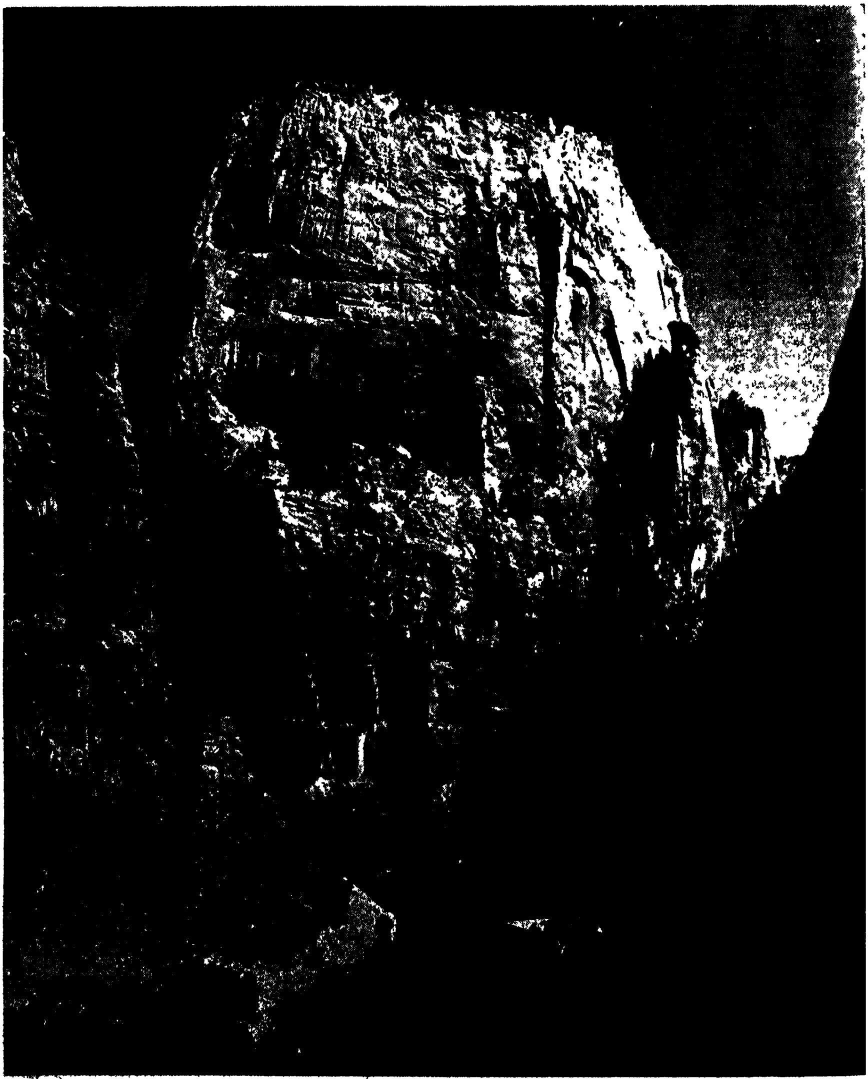

Fig. 176. The Great White Throne, composed of Jurassic sandstone, in Zion National Park, Utah. *Courtesy Union Pacific Railroad.*

throughout the Jurassic seas. A portion of the internal skeleton, shaped like a cigar, is the only part of the animal that is commonly preserved. These skeletal parts are found in vast numbers in some Jurassic formations.

Jurassic dinosaurs. The Jurassic and Cretaceous periods witnessed the climax of reptilian dominance. Among all the various forms of reptiles the dinosaurs were particularly conspicuous. The largest of all the many different kinds were the great swamp-living types. Some of these, like *Apatosaurus, Brontosaurus,* and *Diplodocus,* were more than 80 feet long and weighed 30 or 40 tons. They were forced to spend most of their time in the water because their legs were relatively weak, and they were able to do very little walking on the land. Their heads were small, and their brains were about the size of an ordinary fist. The migratory habits of these animals are amazing when we consider their lack of walking ability. They moved in great herds from one place to another by wading and swimming down the rivers and along the coastal lagoons until they came to the mouth of another river that seemed to offer them food and shelter from carnivorous dinosaurs. Some of the swamp-living dinosaurs had the habit of swallowing stones and retaining them in a gizzard-like digestive apparatus where they were used in grinding up the plant food upon which the animals fed.

Allosaurus was the largest of the Jurassic flesh-eating dinosaurs. These animals reached a length of over 30 feet and were equipped with long, sharp teeth, and powerful jaws. All the carnivorous dinosaurs walked on their powerful hind legs.

Stegosaurus was one of the strangest of all the dinosaurs. These animals weighed as much as 10 tons and had extremely high, arched backs, with two rows of great bony plates running along the dorsal side of the animal from the head to the tail. The head was small, and the brain weighed about 3 ounces.

Sea serpents. Two very remarkable groups of marine reptiles lived in the Jurassic seas. *Ichthyosaurus* resembled a shark, and the legs were modified into flippers like those of a modern porpoise. There was a fish-like fin on the back, and the tail was divided into an upper and a lower fluke. The animal was probably unable to come out of the water to lay its eggs on the land, and so it had developed the remarkable habit, for a reptile, of retaining the eggs inside the body until the young were ready to be born alive. The skeletons of unborn young ichthyosaurs have been found still inside the body of the mother. The carbonized skin of several ichthyosaurs has been found outlining the body around the skeleton.

The *plesiosaurs* had flattened, turtle-like bodies, with long, slender necks and tails. The legs were altered into great paddles with which they propelled themselves through the water. Plesiosaurs are known to have reached a length of over 40 feet, with the neck about 20 feet long.

Reptiles in the air. Among all the thousands of different kinds of vertebrates that have lived during the long courses of geologic time, only three groups have developed the ability to fly. The mammals are represented only by the bats; the birds are descended from a reptile similar to some of the small carnivorous dinosaurs; but within the great reptilian group itself, only one member learned to fly. The oldest flying reptiles have been found in rocks of Upper Triassic age in Europe, but almost nothing is known about their ancestry. Although they were the rulers of the air for several million years, they became extinct at the end of the Cretaceous period.

The smallest known flying reptiles were about the size of a sparrow, and the largest ones had a wing spread of more than 22 feet. The fourth finger was greatly lengthened in all the different forms, and a thin membrane of skin (the "wings") stretched from this finger back to the body and the hind legs. The other three fingers were not elongated. They were fully functional, and the ends were furnished with claws that were used for climbing. The main long bones in the arms and legs had very thin walls and were hollow. This greatly reduced the weight of the animal and made it easier for the reptiles to maintain their bodies in the air for extended periods. Teeth were present in the jaws of the earliest forms, but the later Cretaceous varieties were toothless. Flying reptiles probably walked upon all fours with the fourth finger folded backwards, and the three short functional fingers resting upon the ground. The largest ones had to take off from the edge of a cliff or the top of a dead tree, while the smaller ones required a slighter elevation—or they might have leaped into the air as many birds do.[4]

Thousands of broken bones of different kinds of flying reptiles have been found in certain localities, especially in Cretaceous rocks of England. The animals were apparently gregarious and lived in great flocks like some of the birds.

The birds or feathered reptiles. The earliest known members of the bird family have been found in the celebrated Jurassic lithographic stone of southern Germany. Two skeletons were discovered together with impressions of feathers on the wings and tails. The body was probably covered with soft contour feathers which are difficult to preserve even as imprints. The reptilian teeth in the jaws, the long bony tail, and the functional fingers on the wings, each one tipped with a claw, reveal beyond a doubt that the immediate ancestor of these Jurassic birds was some form of small carnivorous reptile that walked on its hind legs. The feathers alone distinguish the Jurassic birds, *Archaeopteryx* and *Archaeornis,* from some of the small dinosaurs.

The lithographic limestone of Bavaria, in southern Germany, has preserved a great many remarkable fossils of both invertebrates and vertebrates, in addition to the only known Jurassic birds. The fauna includes flying reptiles, showing impressions of the wing membranes, the marine reptile *Ichthyosaurus* with its carbonized skin, crocodiles, and turtles. The fine-grained mud, from which the rock was made, must have accumulated in quiet, shallow water, probably in lagoons along the shore of the Jurassic sea. This lithographic stone was once widely used in printing (it was actually the earliest form

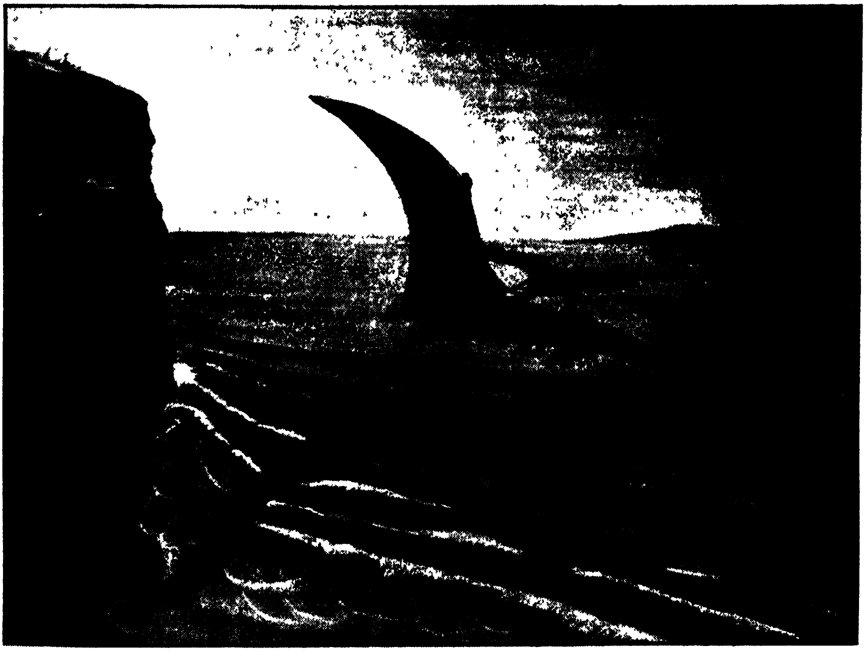

Fig. 177. Pteranodon, a flying reptile, found in the Cretaceous chalk of Kansas. ***By John Jesse Hayes.***

of what is now known as offset printing). Subsequent technical developments have provided substitutes for this limestone and now the rock is quarried chiefly for the valuable fossils that it contains.

Mammals. Fossil remains of Mesozoic mammals are rare, and it is

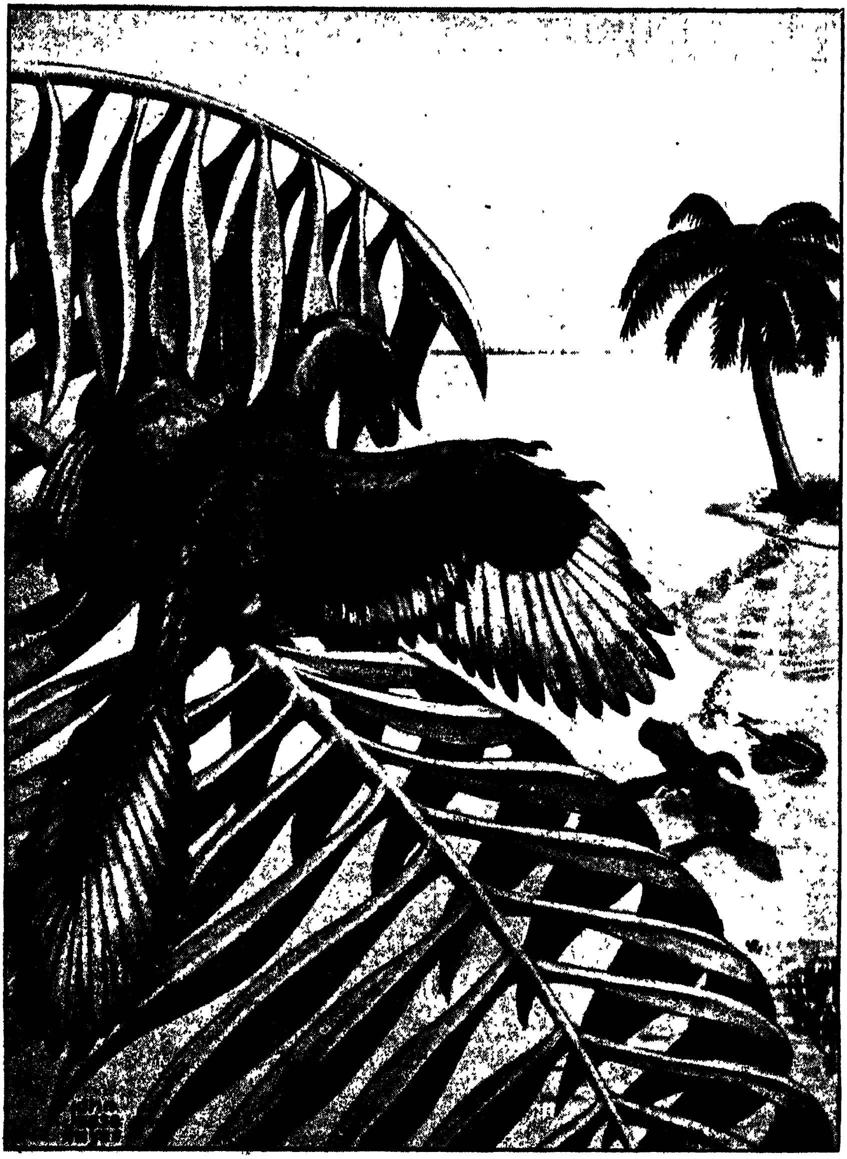

Fig. 178. Archaeornis, a Jurassic bird from the lagoon of Solenhofen, Bavaria. *By John Jesse Hayes.*

difficult to explain this scarcity, because the living animals must have been abundant in certain places. The reptiles were so numerous during most of the Mesozoic era that the small mammals probably found the competition with them too keen in the warm lowlands. This situation must have caused the mammals to take refuge in the cool highlands where their enemies were less numerous. The higher lands, however, are not favorable places for the preservation of organisms as fossils, because deposits are fewer and erosion more vigorous.

The Cretaceous Period. The last great North American epeiric sea invaded the continent in the Upper Cretaceous period, when about half of the land was submerged during the various advances and retreats of the water.

The old Land of Appalachia had for a long time been a barrier to any invasion of sea water from the Atlantic ocean to the east, but now the Cretaceous sea moved westward across Appalachia, and may even have covered a portion of the peneplained Appalachian Mountain area. The deposits left by this eastern invasion are included in the Potomac group of rocks, and they are found from New Jersey to Georgia.

Cretaceous rocks are widely distributed over the western part of North America. They include the Dakota group, with its characteristic dark brown sandstone member, which is an important source of water in several parts of the Great Plains. This sandstone, and the softer under-lying rocks, are now standing at steep angles for many miles along the eastern front of the Rockies in Colorado and Wyoming, where they form long ridges called hogbacks. The Colorado group includes an argillaceous limestone-and-shale member called the Niobrara chalk, which is famous for its vertebrate fossils.

Chalk is exposed for many miles along both sides of the English channel, and some of this great deposit is composed chiefly of the white calcareous shells of one-celled animals called Foraminifera. The weathering of extensive deposits of Cretaceous sandstone has furnished most of the sand found in the Sahara desert of North Africa.

The Laramide Revolution reached its climax in the late Cretaceous and produced a vast range of mountains that extended along the entire western interior portion of North America. Many of the great structural features that were formed during this revolution may still be seen. The Front Range in Wyoming and Colorado was originally a wide arch, until some parts, now mostly valleys and parks, were downwarped. The Big Horn Mountains in Wyoming and the Black Hills in South Dakota and Wyoming were formed as great dome-like elevations at the time of the Laramide revolution. Eastward movements along some of the great thrust planes continued into the early Tertiary period.

There was intense igneous activity in the Laramide Ranges while the folding and faulting were going on, and it included the intrusion of some batholiths. The vast copper deposits of the Butte, Montana, district are associated with one of these intrusive masses.

The entire western side of South America, for a distance of 5,000 miles, was upheaved into mountains at the same time as the Laramide revolution.

Mineral deposits. Extensive fresh water swamps were formed over large areas of the Rocky Mountain and Great Plains regions in the Late Cretaceous, and great thicknesses of plant material accumulated in these swamps. This material was slowly converted into coal that varies in kind from lignite to anthracite. There are about 900,000,000,000 tons of this coal still in reserve. Petroleum is produced from Cretaceous rocks in Texas, the Rocky Mountain states and Mexico. Besides the copper at Butte, Montana, Cretaceous rocks in the Rocky Mountain area also produce lead, zinc, gold, and silver.

Life of the Cretaceous Period. Modern types of flowering plants must have been in existence during a part of the Jurassic period, but very little is known about them in that period. They appeared for the first time in great abundance during the Cretaceous period, in whose rocks most of the present-day types are represented by fossil forms. There were extensive forests composed of such familiar trees as the willow, oak, maple, walnut, birch, sassafras, magnolia, and sequoia. Shrubs, grasses, and cereals also made their appearance at this time. The great spread of all these different kinds of modern plants in the Cretaceous period had a most important influence on the evolution of the browsing and grazing mammals that were so abundant in the Tertiary. It is probably true that without this readily available supply of nourishing food the mammals would not have attained their position of world-wide importance.

Modern types of bony fishes originated in the Jurassic and became abundant in the Cretaceous, but reptiles were still the dominant vertebrates. *Archelon* was a giant marine turtle measuring 12 feet across the large front flippers. The *mosasaurs* were "sea serpents" with long, slender bodies that reached a length of about 45 feet. Flying reptiles have been found in the Niobrara chalk of western Kansas. *Pteranodon* had a wing spread of 22 feet. These same rocks have given us the skeletons of a great aquatic bird called *hesperornis.* The wings were reduced to vestiges, there were teeth in the jaws, and some of these birds were six feet long.

The greatest of all the flesh-eating dinosaurs, *Tyrannosaurus rex,* lived in the Cretaceous. The fine skeleton in the American Museum of Natural History is 45 feet long and almost 20 feet tall. This frightful creature was equipped with powerful claws and long teeth for rending and killing any animal that it encountered. It was truly the "king of the tyrant lizards."

Triceratops was a four-footed herbivorous dinosaur that was far bulkier than an elephant. Some skulls have been found measuring 9 feet long. The great horns, one over each eye, pointed forward and were useful weapons. There was a strange backward expansion of the skull over the neck which offered protection to the animal in its fights with *tyrannosaurus.*

The duck-billed dinosaurs led semi-aquatic lives, wading and swimming in the rivers, lakes, and swamps. They walked on their hind legs and their short front legs were used for holding objects. Numerous skin impressions of these dinosaurs have been found. One remarkable specimen in the American Museum of Natural History has preserved an imprint of almost the entire body.

Mammals were numerous, but their fossil remains are still scarce. Cretaceous marsupials, similar to the modern opossum, have been found in the Belly River beds of Canada. Small shrew-like insectivores lived in Mongolia and North America. These animals were particularly important because some member of the group may have been the ancestor of the primates: The modern pen-tailed shrew is classed as a primate.

THE CENOZOIC ERA

The Tertiary Period. Some of the familiar features of the earth's surface have been inherited from the distant past, but most of the present topography originated during the Tertiary period and some of it within the last epoch of that period.

Thick marine Tertiary sediments were deposited in the Pacific border area and along the Atlantic and Gulf Coastal plains. At the same time a great series of continental beds was deposited in the western part of the United States. These non-marine sediments contain a fine record of Tertiary mammals that is probably unexcelled by the rocks of any other continent.

The Great Plains are located along the eastern front of the Rocky Mountains and stretch eastward well into the Dakotas, Nebraska. and Kansas. This great area, now somewhat dissected, was veneered during the Tertiary by sediments brought from the Rocky Mountains and deposited by streams that flowed in a general easterly direction. Vast herds of bison and other grazing animals once lived on these plains, and, wherever water is obtainable, the soil is fertile.

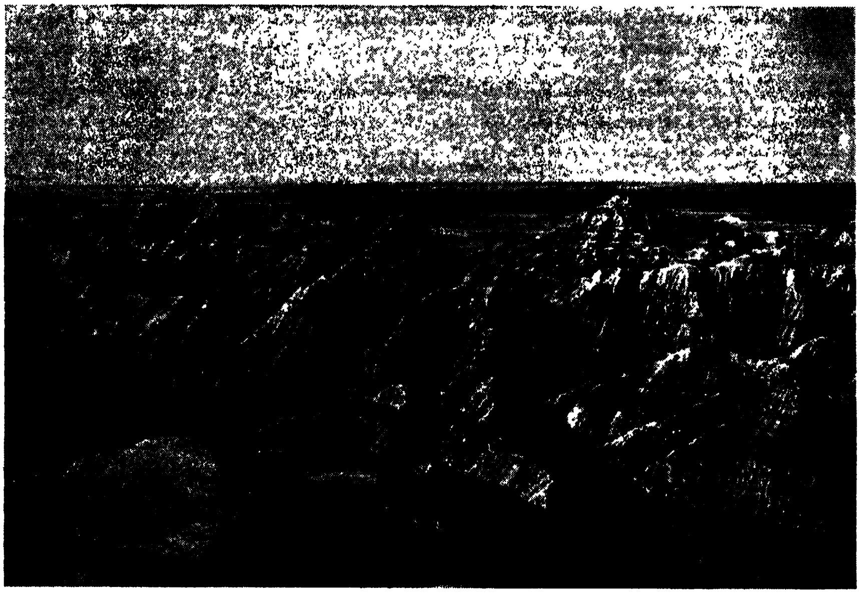

Fig. 179. Big Badlands of South Dakota, showing deep erosion of non-marine Tertiary beds. *By M. V. Denny.*

Many of the most beautiful and striking scenes in the United States have been eroded out of Tertiary deposits. The Badlands of South Dakota consist of clay and silt, with considerable volcanic ash and some cross-bedded sandstones, which were deposited in the channels of streams. Bryce Canyon, in southern Utah, is one of the most brilliantly colored scenic places in the entire country. The rocks are of Tertiary age.

Tertiary volcanoes. A long period of volcanic activity began in the western part of North America about the time of the Laramide revolution and has continued intermittently down to the present. Many of the loftiest and most beautiful mountains in the west are either extinct or dormant volcanoes. Some of these are Mount Shasta in northern California, Mount Hood in northwestern Oregon, Mount St. Helens and Mount Rainier in southwestern Washington, and Mount Lassen, the famous California volcano that erupted with great violence in 1914 and 1915. It is very difficult to tell whether a volcano is dormant or extinct, some of those which have not erupted within very recent times may become active at any time. There are many recent volcanoes around the region of Flagstaff, Arizona, and some of them were active not more than a few hundred years ago. One of these volcanoes, Sunset Crater, hurled out so much ash during a recent eruption that the Indians who were living in the region had to leave the country for several years. Craters of the Moon National Monument, in southern Idaho, is a volcanic field so fresh that the

Fig. 180. Mt. Rainier, an extinct volcano, in southwestern Washington. *Courtesy Washington State Progress Commission.*

surfaces of the many lava flows show no appreciable weathering. The Columbia River Plateau covers about 200,000 square miles in the northwestern part of our country. This vast area has been formed by a long series of lava flows that poured out intermittently from long fractures in the earth's crust. The flows vary in thickness from less than 10 to more than 200 feet, and the total thickness is more than a mile in many places. Most of the rocks in the Yellowstone National Park region are of volcanic origin, and hot, buried lava only a short distance below the surface is responsible for the hot springs and geysers.

How the modern Appalachian Mountains were formed. As soon as the folds of the first generation of Appalachian Mountains began to rise near the end of the Permian period, the many forces of weathering and erosion attacked them with increasing vigor as the hills rose higher and higher. At first the mountains were elevated at a faster rate than they were being worn down, but finally when the mountain-making forces had exhausted themselves, erosion became dominant and by the middle of the Mesozoic era the original Appalachians had been largely reduced to a low, gently rolling peneplain. Here and there a few erosion remnants or monadnocks, such as the Great Smokies, rose above the general level surface of the plain.

When the widespread Cretaceous sea invaded the continent of North America it probably covered a great portion of the original Appalachian Mountains area and deposited a comparatively thin veneer of sediments over the old peneplain surface. Then, towards the end of the Cretaceous period, the peneplain was lifted vertically into a long, narrow arch, and the rivers, which flowed in southeastward meandering courses into the Atlantic ocean, were rejuvenated and began to dissect the intermittently rising plain. All the agents of weathering and erosion became more vigorous in their activities. The softer rocks in the peneplain were eroded faster than the harder rocks, and finally the resistant formations, such as the Medina sandstone, were left standing in high relief above the more easily eroded rocks, to form the present ridges and mountain peaks of the modern Appalachian Mountains. The rise of the peneplain was so slow that most of the rivers were able to maintain their original courses. They have cut the present water gaps through the ridges. Some of the smaller and weaker streams were turned aside and flowed along parallel to the emerging ridges, thus forming the present drainage pattern of the Appalachians. Some remnants of the original great peneplain may still be seen at the tops of the ridges, which all rise to about the same level. The vertical uplift also carried the various monadnocks to higher elevations; some of the present peaks in the Great Smokies rise to heights of more than 6,000 feet above sea level. Erosion is still wearing away the Appalachian Mountains and eventually they will once more be peneplained.

The story of the modern Rockies. When the original Laramide Mountains were upheaved, in the Late Cretaceous and Early Tertiary, many of the down-warped portions became broad valleys or park-like areas, which still persist. During the wearing down of the Laramide ranges, some of the sediment that was being eroded from the hills was carried down into the nearby valleys and deposited there. As the ridges and peaks were slowly reduced in height the deposits in the valleys or basins became thicker, and finally some of the lower parts of the ranges were actually buried beneath sediments that were derived from the mountains themselves. Considerable portions of the Laramide mountains must have been reduced to a comparatively low level, but some of the higher ranges always stood a few thousand feet above the surrounding country. Many of the great rivers in the Southern Rockies, such as the Big Horn, the Arkansas, and the Gunnison, had established portions of their courses across the sediment-filled basins and the buried parts of the ranges. Then broad vertical uplifts began in the old Laramide area, and the rivers were rejuvenated. Their increased velocity enabled them to cut down into the sedimentary covering, and when they encountered the buried parts of the ranges they were able to maintain their courses because the rise of the land was very gradual. As the vertical uplift continued intermittently, many of the rivers finally cut deep gorges or canyons which lead through the present ranges. Some of the valleys still have considerable thicknesses of the original sediments along the sides, but most of the sedimentary material has been carried away. The last of the series of vertical uplifts in the Rocky Mountains occurred during the late Pleistocene, only a comparatively short time ago, and the present Rockies are thus partly the result of the vertical uplift and dissection of older ranges of hills. The Royal Gorge of the Arkansas River, the Black Canyon of the Gunnison, and the Big Horn Canyon are only a few of the impressive scenic features that have been formed during this last stage in the history of the Rocky Mountains.

The Basin Ranges in Nevada and the modern Sierra Nevada Mountains are great tilted earth blocks that have been dissected to form the present hills. Mountain building in the Pacific border area is still in progress, as is shown by the recent folding and earthquakes in that region.

Climate of the Cenozoic Era. The climatic conditions during at least the first half the the Tertiary period were so mild that tropical and sub-tropical conditions prevailed as far north as the boundary between the United States and Canada. The early Tertiary flora of Greenland indicates a climate similar to that of Virginia at the present time. Large crocodiles were able to live in Minnesota during the Eocene, and the plants found in Miocene volcanic ash at Florissant, Colorado, are similar to those growing in the Gulf states today.

The Great Plains became semi-arid in the late Tertiary, when the Rocky Mountains were re-elevated and became a barrier to moist westerly winds.

Cenozoic economic deposits. Great cylindrical masses of salt have been forced upward through Tertiary sediments of the Gulf Coast from some unknown depth below. The sediments near

Fig. 181. East side of Garden Wall in Glacier Park, Montana. ***By permission Spence Air-Photos.***

the salt have yielded petroleum in several places. Petroleum is found also in Miocene and Pliocene rocks in California. Oil will be recovered some day from the carbonaceous Green River shales of northwestern Colorado and nearby parts of Wyoming and Utah. The great Baku oil field of the U.S.S.R. is in Tertiary rocks, and formations of the same age are producing petroleum in the Dutch East Indies, Rumania, Venezuela, Iran, and Iraq. Tertiary coal is found in Montana, Wyoming, Washington, and Oregon.

The Jurassic gold-bearing quartz veins in the Sierra Nevada Mountains of California were uncovered during Cenozoic time. Subsequent weathering separated the gold particles from the quartz and formed the celebrated placer gold deposits that caused the great gold rush to the Pacific coast in 1848 and 1849. Stream gravels in California have produced more than 1,000,000,000 dollars' worth of gold and they are still being worked in many places.

The gold, silver, and copper ore deposits in some of the famous mining camps of the West are located in Tertiary rocks. Gold in the Cripple Creek district of Colorado is associated with Tertiary igneous rocks. The gold and silver in the famous Comstock Lode near Virginia City, Nevada, were discovered in 1858. Ouray, Telluride, and Creede are mining towns located in the San Juan region of southwestern Colorado. The copper ore at Bingham Canyon, Utah, is associated with late Mesozoic or early Cenozoic rocks.

Continental glaciers of the Pleistocene. Continental glaciers have appeared at infrequent and irregular intervals during the course of geologic time. It is quite possible that geologists have not discovered the evidence for all the glacial ages of the past. but they do not seem to have been very numerous. The exact causes which bring about the spread of such vast sheets of ice are not well understood, but certain facts can be noted. According to one theory the continental glaciers of the Pleistocene in North America started as mountain glaciers in the highlands along the eastern side of Canada. The supply of snow was brought in by moist winds from the Pacific and the Gulf of Mexico region. Finally the mountains in Quebec, Labrador, and Baffin Land were completely covered, but still the snow kept on falling and turning into ice. In places where the snowfall was exceptionally heavy, great ice domes were built up. One of these, called the Labrador Cap, was east of Hudson Bay, and the Keewatin Cap lay west of the Bay. At the time of its maximum extent, the ice is known to have spread westward almost to the foot-hills of the Canadian Rockies, and south and southwestward to the Ohio and Missouri Rivers. Nearly all of Canada was buried under a sheet of ice that must have been two miles thick in places.

The entire Pleistocene epoch was not subject to a glacial climate. Instead, the ice formed four times, and after each stage of glaciation there was a warm interval probably twice as long as the period of glaciation. The present may be the beginning of one of the warm intervals which will be followed, after several thousand years, by another advance of the ice, or perhaps the great Ice Age may be definitely coming to a close. If the latter condition is true, all the ice in Greenland and on the Antarctic continent will eventually melt and the level of the oceans everywhere will be raised at least 100 feet. This rise will inundate large areas along the Atlantic and Gulf Coastal Plains unless those areas are uplifted in the meanwhile.

Two main types of deposits resulted from the glaciation. Unstratified and unassorted material was deposited directly by the ice when it began to melt. Most of these till deposits are found in the great moraines which mark stages in the retreat of the ice front. The present topography in southern Michigan is rough in those areas where the moraines were formed and relatively smooth elsewhere. Water from the melting ice carried great quantities of sand and gravel away from the glacier front and this sediment is roughly stratified.

The Great Lakes. The present Great Lakes were formerly river valleys and basin-like depressions the slopes of which were modified by the ice as it moved to the south and west. These depressions were filled with water when they were finally uncovered after the recession of the last, or Wisconsin, ice sheet. When the retreating ice front uncovered the northward-facing Niagara escarpment, Niagara Falls came into existence. The shape of the Great Lakes has not altered much since the final retreat of the ice, but the water level once stood more than 50 feet higher than it does now. These glacier-born lakes are of enormous importance as waterways.

The very rich wheatlands in North Dakota, Minnesota, Manitoba, and Saskatchewan were once the bottom of Lake Agassiz, a large body of fresh water that covered about 110,000 square miles. Great Salt Lake in Utah is a small remnant of an older fresh-water lake called Bonneville, that originally covered 20,000 square miles and had a maximum depth of 1,000 feet.

The scouring and plow-like action of the glaciers removed the rich topsoil from certain areas in Canada and deposited it over wide stretches in the northern part of the United States.

Such enormous sheets of ice rendered the glaciated regions themselves uninhabitable, forcing many animals to migrate southward into warmer regions. The United States became a place of refuge for animals that had formerly lived in Canada, and this crowding together of many types of life, that would not live together under normal conditions, was probably one of the causes of the wholesale extinction of numerous groups of mammals that had survived in North America until the Pleistocene. The climate in the northern part of the United States during the glacial stages must have been about like that of Greenland today, and the cooling effect of the glacier must have been felt for many miles south of the ice front.

The Pleistocene is of particular significance because many important steps in the evolution of man occurred during this epoch. Several different races of men came into Europe, and late in the Ice Age the modern type of man appeared.

Life of the Cenozoic Era. Towards the end of the Mesozoic era, many great groups of reptiles became extinct, and, as the reptiles disappeared from their warm lowland haunts, the mammals appeared in ever increasing numbers until they became the rulers of the earth. The mammals, because of their ability to resist the cold, were able to live in many places that had not been accessible to the reptiles. These warm-blooded, active animals thus completed the conquest of the land, which the lobe-finned fishes had started back in the Devonian period. The birds, another group of warm-blooded, feathered animals, reached their climax in size during the Cenozoic. Giant forms lived in the United States, South America, New Zealand, and Madagascar, and some of them became extinct only within recent times.

The story of the horse. The known geologic history of the horse family began about 60,000,000 years ago with the appearance in the United States of the famous *Eohippus* or "Dawn Horse." This little animal was less than a foot high, or about the size of a fox terrier. He had four functional toes on his front feet and three on his hind feet, and the nails were hoof-like. His teeth were small and the crowns low, indicating a diet of soft plant food. He probably browsed in the woodland areas, or in the bottom lands along the rivers where food was abundant. Many intermediate forms between *Eohippus* and the modern *Equus* are known which reveal a gradual increase in size, a loss of the lateral digits, and an increase in length of teeth. *Mesohippus* was about the size of a large dog, and was a three-toed animal, with the middle digit larger than the lateral ones. The first one-toed horse, *Pliohippus,* appeared in the Pliocene epoch, and there were many members of the genus *Equus* in the Pleistocene. Some were small animals, about as large as a modern pony, while others were larger than the biggest modern work horse. The wild horse is supposed to have become extinct in North and South America during the late Pleistocene, and the two continents were repopulated by the descendants of horses brought over by the Spanish Conquerors and later explorers. True wild horses are still found in Africa and certain parts of Asia.

The story of the elephants and mastodons. The elephants and mastodons are related forms that sprang from a common stock which had its origin in Northern Africa during Eocene time. The earliest known member of the race is *Moeritherium,* an animal about three feet high at the shoulder and without tusks or trunk. This form was probably semi-aquatic, and it lived in the region of the ancient Nile delta where plant food was easily obtained. The most important anatomical changes in the elephant group, from *Moeritherium* to the modern type, were a gradual increase in size, the appearance and development of the tusks and trunk, and a considerable increase in the height of the skull without a proportionate increase in its length.

The first mastodon to reach the United States came in the Miocene epoch by way of the Alaskan-Siberian land bridge. The climate in the far north must have been considerably warmer at that time than it is at present. The American mastodon, common all through the eastern part of the United States, was a fine, stocky animal that stood from seven to nine feet high. Most of its food was obtained by browsing in the forests and brush-covered lowlands. Mastodon bones have been found in very late Pleistocene and Recent swamps, with some of the organic matter still inside the bones and with pieces of cartilage still fastened to parts of the skeleton. It is uncertain whether these animals possessed the dense undercoat of woolly hair such as the woolly mammoth had. The tufts of brown hair that have been reported associated with the skeletons of mastodons are probably strands of algae that greatly resemble hair. Some of the skeletons have been found with quantities of undigested plant food between the ribs, in the former position of the stomach. The plants were from spruce and hemlock trees. The last American mastodon must have disappeared within comparatively recent times. An unusually complete skeleton of one of these animals was discovered near Owosso, Michigan, and is now mounted in the University of Michigan Museum.

Several types of mastodons and elephants lived in the United States during the latter part of the Tertiary period. The great Imperial Mammoth lived in the warmer regions of the south and has been found from California to Texas and Mexico. Some members of this group reached a height of 14 feet. The Jeffersonian mammoth lived widely through the Mississippi Valley region, and the woolly mammoth ranged from Siberia and Alaska into the New England states. The extinction of the elephants and mastodons, together with that of many other mammals, has never been explained.

The geologic history of man. About 60,000,000 years ago there appeared a remarkable group of mammals that was destined to dominate the entire earth more completely than it has ever been ruled before. This was the group called the *primates.* At first these animals were small, tree-living forms, with no great physical strength, and they gave little evidence at first of their coming importance in the world. Very soon, however, the primates began to develop those special powers that have culminated in the higher types of modern men. These powers were connected with an extraordinary development of the brain and the hands which have enabled man, the highest primate, to develop an amazing number of tools and scientific devices for special purposes. Man's dominant position today is due largely to his mastery of tool making and tool using.

The first primitive New World primates came to North and South America in the Early Tertiary, but some climatic change, soon after the Eocene epoch, caused them to retreat to Central America and the tropical parts of South America where many types of monkeys are found today.

About the middle of the Tertiary period certain groups of primates gradually abandoned their arboreal habitats and adapted themselves to a life on the ground, while within this group some very special primates started to walk on their hind legs and slowly assumed the upright posture. The first evidence of this upright-walking man-ape is found on the island of Java, where the remains of the celebrated *pithecanthropus erectus* have been discovered. A very good reconstruction of the skull of the Java specimen has been made by putting together parts of several incomplete skulls. The characteristics include a low, sharply retreating forehead, heavy brow ridges, a receding chin, and a cranial capacity of about 900 cubic centimeters. The modern types of thigh bones that have been found in the same layers of gravel with the skull fragments indicate that the people of the Java race had acquired the upright posture Pithecanthropus lived about 500,000 years ago. According to current knowledge the race originated on the mainland of Asia and migrated to Java while it was connected to the continent.

Several skulls of a form closely related to pithecanthropus have been found in some caves near Peking, China. This race has been named *sinanthropus pekingensis.*

The great Neanderthal race came into western Europe during the warm interval that preceded the last glacial stage and lived in caves all the way from the Mediterranean region to southern England. Their habit of burying the dead is responsible for a considerable number of well-preserved skulls and several fairly complete skeletons. The Neanderthal men were seldom more than five feet four inches tall, while the average height of the women was about five

Fig. 182. Pithecanthropus in a middle Pleistocene jungle of Java. Tapir and tiger remains have been found in the same region. ***By John Jesse Hayes.***

feet. They had great power in their arms and shoulders, and the difficulties of their environment tended constantly to weed out the weak and unfit. Their thigh bones were strongly curved forward, which shape caused them to walk with their knees bent and a slightly stooping body posture. Their arms were probably swung back and forth in front of the body instead of along the sides as in most modern races. They dressed in the skins of different animals and slept on piles of skins in the caves. Difficulties in lighting the caverns made it most convenient for them to occupy only the outermost parts of the caves, close enough to the entrance so that the smoke from their fires could escape.

Neanderthal man lived entirely by hunting, and his best weapons were wooden, flint-tipped spears, and slings which were used to propel small, rounded stones. He also had hand axes or hatchets which could be used when he encountered an animal at close quarters. Pitfalls and traps were probably employed in catching such large animals as wild cattle, horses, reindeer, bison, and even elephants. He was constantly on his guard against the giant cave bear, especially in the fall when these animals were seeking caves in which they might hibernate. The final fate of the Neanderthal race is not known. Its members may have fallen in battle with the more modern types of people who came into Europe late in the Pleistocene, or they may have been driven from their caves and villages into inhospitable places farther to the north and northeast where they finally perished. The question of racial mixture between the Neanderthal people and their more modern successors cannot be demonstrated, although there is the possibility that it did occur occasionally.

The Cro-Magnon or modern type of people began to filter into Europe toward the close of the Pleistocene, after the glacier had retreated to the Scandinavian highlands. The climate was still cold, and many of the old caves were used as shelters, but villages sprang up in many places that became, more and more, centers of permanent habitation. The houses or huts probably had a framework of saplings or slender branches with a covering of skins or thatch. There were many different tribes within the Cro-Magnon race, and the individuals varied just as people do today. Some skeletons are those of persons who were more than six feet tall, while others are only of average height. All the tribes lived by hunting, and animals of many kinds were usually abundant. Wild horses, cattle, reindeer, and bison furnished a great deal of their food. Around one of their village sites in France there were found the bones of nearly 100,000 horses piled up in long rows and great heaps.

Their hunting weapons included the spear, the bow and arrow, and the spear thrower, all implements that are still in use among primitive people. The necessity for securing food kept the men on the hunt nearly every day, but with the approach of winter they probably staged a grand hunt in which every ablebodied person cooperated. These seasonal hunts were preceded by great ceremonies which were held in some of the innermost recesses of the caves. Pictures of the animals that they hoped to kill were painted or carved on the walls of the caverns, and magic ceremonies were performed in the presence of the chief of the tribe, the hunters, and the medicine men. Hundreds of these paintings and carvings are still found in the caves of southern France and northern Spain and, while most of them are very crude, some show considerable artistic ability.

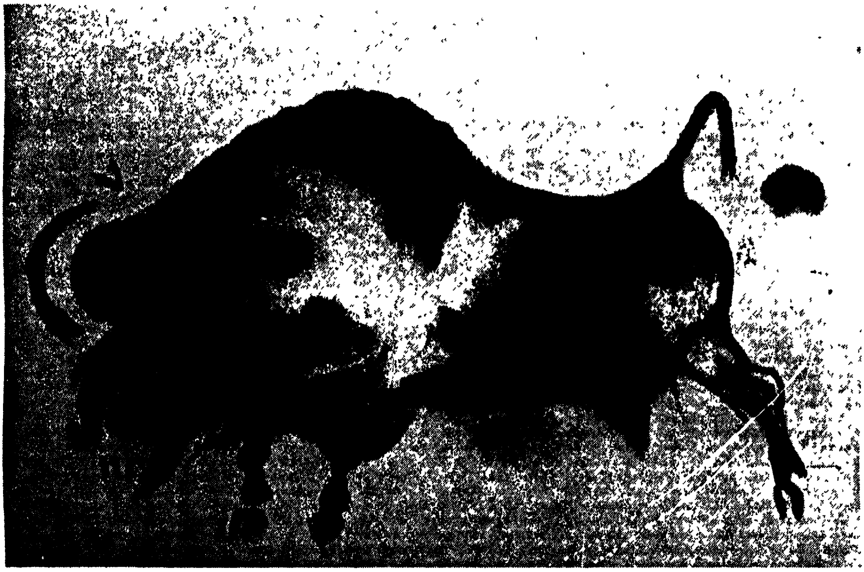

Fig. 183. Bison painted in black on the walls of the Font-De-Gaume cavern in southwestern France.

The Men of the Old Stone Age continued into the New Stone Age without any important physical changes in the people themselves, but rather in their methods of living. The art of making pottery was discovered, and, with the development of agriculture and the domestication of animals, man no longer found it necessary to spend so much of his time in the pursuit of game. The population increased, neighboring tribes joined to form nations, and man's problems became even more complex with the constant clash of national interests.

The Eskimos and Indians came to North America from Siberia, but the time of their arrival is not known. Indian spear-points and arrow-heads have been found with the bones of extinct elephants and bison, but it is still impossible to determine just when these animals were killed. The Eskimos still use many of the same types of weapons and implements that the Old Stone Age men used, and their living conditions are very primitive. Some tribes of American Indians are now extinct, while others are increasing in numbers.

Man's future is apparently in his own hands, because he is the first animal that has been able to control and modify its environment to a great extent. He has done so by means of a vast number of mechanical devices that have made him almost independent of the climate and have enabled him to produce food and other necessities beyond his actual needs. However, man the product of millions of years of evolution, is still an animal. His predatory instincts are still as strong as ever, and therein seems to lie the greatest danger to the human race. Man has discovered many of the deepest secrets of nature, and he is on the verge of unlocking the door that leads to the ultimate construction of matter itself and the mystery of living material or protoplasm, and yet he has not learned how to control himself and live with other members of the human race. Unless man learns how to produce better human beings, as he has learned how to produce better horses and cattle, he will become as extinct as the dinosaurs. Biological laws are inexorable.

PART FIVE

Practical Applications

Geology is not only a cultural science, but also a very practical one. Applied geology is referred to as economic geology. *Branches of this science, the names of which are self-explanatory, are mining geology, petroleum geology, and engineering geology.*

The subsequent chapters emphasize the role played by the economic geologist in the search for mineral deposits and in solving various problems encountered in engineering projects. The reading of the two chapters which follow will not make one an economic geologist, but it may give some insight into the methods used by members of the profession, and an appreciation of the practical value of the science.

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CHAPTER 17

The Search for Mineral Deposits

THE METHODS FOLLOWED IN SEARCHING for new mineral deposits vary with the type of deposit sought. For example, the procedure in hunting for new oil pools is far different from that used in looking for goldbearing veins. The methods followed in prospecting for sedimentary deposits, however, are practically the same whether the material sought is coal, gypsum, or any other stratified rock.

The origins of the various types of mineral deposits are described in pertinent chapters in Part Two. A classification of such deposits is given below. The figures in parenthesis refer to the chapters in which the genesis of the deposits is discussed. Because mineral deposits are earth materials just as much as rocks, they are subject to the same general classification.

CLASSIFICATION OF MINERAL DEPOSITS

- Igneous (*10*)
  - Magmatic deposits
  - Pegmatites
  - Hydrothermal veins
  - Hot spring and fumarole deposits
- Sedimentary (*9*)
  - Organic deposits
  - Inorganic sediments
    - Precipitated compounds
- Metamorphic (Regional) (*11*)
- Secondary
  - Deposits formed through weathering processes (*3*)
  - Deposits formed by ground waters (*4*)

The subdivision "Organic deposits," under the Sedimentary group, includes derivatives of organic sediments, such as oil and gas, in addition to coal and other deposits of direct organic origin.

Placer deposits may be formed through the activity of running water, shore line processes, and even the wind; consequently they are described in the chapters in Part Two that deal with those phenomena.

Secondary deposits consist either of minerals formed from preexisting materials through processes at work at or near the earth's surface, or of minerals concentrated through the removal (leaching) of associated valueless material. The original source of all matter in the earth's crust is the magma; therefore, strictly speaking, all mineral deposits except those falling in the igneous class are secondary. However, in this classification, deposits which are formed through deposition of sediment or regional metamorphism are classified separately.

This classification does not include one mineral resource, *ground water,* which is of great importance to mankind. The occurrence of ground water, and methods of prospecting for it, are given in Chapter 4.

Mineral deposits, in addition to being classified by origin, can be classified also according to type of material. Major groups by this arrangement are (1) metals, commonly referred to as ore deposits, (2) non-metals, and (3) mineral fuels, which include mainly coal, oil, and gas.

Various methods employed in prospecting for widely differing types of deposits, including ore bodies, coal (and other bedded rocks), oil, and mineral bodies in metamorphic rocks, are given in the following sections. Oil has separate treatment, for, although it occurs in sedimentary rocks, a specialized technique must be followed in prospecting.

PROSPECTING FOR ORE BODIES

The search for new mineral deposits can be divided into two branches. One is the discovery of new districts, and the other the discovery of new ore bodies or enlargements of previously known ore bodies in already established mining districts. The latter branch of economic geology is called *mining geology.* Up to the present time, the use of geologic method has been more effective in mining geology than in the search for new districts.

Surface prospecting methods.

In the past, prospecting has been a matter of keen observation of rock exposures by individuals largely untrained in the science of geology, coupled with a fair share of luck. That luck was an important element in the discovery of the great bonanzas of the last century is amply attested by the stories and folklore of the mining camps of the western United States. Regarding one of the discoveries that made Leadville, Colorado, a famous mining district in the latter half of the 19th century, T. A. Rickard, able chronicler of American mining history, says:

> The most important was the consequence of pure accident. Two prospectors were grubstaked, or provided with tools and food, by a man named Tabor, who had a store and was the local postmaster. He was to have the half of anything that the two prospectors, Rische and Hook, might find. Among their provisions was a jug of whiskey, which proved so inviting that they decided to drink it before they had gone more than a mile from the camp. When they had done so, they concluded that the spot at which they had halted, on Fryer Hill, was as good a place as any other for sinking a shaft. At a depth of 30 feet they struck the rich orebody of the Little Pittsburg mine, this being the one point of all others on the hill where the ore lay nearest the surface.[1]

This method of discovery, although singularly successful for Rische and Hook, is not recommended.

New mining districts are still being discovered by prospectors, but because most of the ore bodies readily recognizable at the surface have already been discovered, the rate is very much less than what it was a few decades ago. At the same time, geological methods have developed to the point where they can be used in the discovery of new districts also, but they may never be as successful as the old-time prospector, because they came into the field after so many great ore deposits had been discovered.

The most useful tool of the geologist engaged in searching for new areas of mineralization is the geologic map. Such a map shows by colors or patterns, or both, all of the different types and ages of rocks which reach the surface. It also shows the relationship existing between these different rock types, and the structure of the rock formation. In the present-day exploration of new regions, such as Newfoundland and northern Canada, the first step has been the preparation of a geologic map, and as a result the search for new mineral deposits has been notably successful in these areas.

Placer prospecting. Minerals such as gold and diamonds, which are both more resistant to decay and heavier than the common rock-forming minerals, after being released from their source rocks by weathering, become concentrated in placer deposits in stream beds, especially where an abrupt decrease in gradient takes place. Prospecting for placer deposits continues to be largely a matter of hard work, excavating through the stream alluvium and panning the sands and gravels lying just above the bedrock surface. However, geological knowledge enables one to seek out the drainage basins most favorable to the presence of alluvial gold, or diamonds, or whatever is being sought. Geological maps, if available, should be studied and the river systems that drain only sedimentary rock areas rejected from further consideration. The search should be confined to streams that drain districts in which intrusive igneous rocks are known to exist. Furthermore, cognizance should be taken of the varieties of igneous rocks exposed. If placer diamonds are sought, the chances for success are many times greater if volcanic necks occur within the drainage basin, for volcanic necks have been the source of most diamonds. (However, diamond-containing volcanic necks are relatively scarce; most of these rock bodies are barren.) Platinum placer deposits are confined to drainage basins in which basic igneous rocks are exposed. Even gold is more prone to occur where certain types of intrusive igneous rocks are found.

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[1] Rickard, T. A. *A History of American Mining*, p. 130. New York: McGraw-Hill Book Company, 1932.

Lode prospecting. For ore deposits that contain minerals liable to be concentrated in stream placers, the placers themselves aid in discovering the vein. Miners have discovered gold-bearing lodes by working upstream and panning the stream gravels at fairly close intervals until the grains of gold in the pan reach maximum coarseness and the gravel farther upstream proves to be barren. Then the procedure is to prospect up the sides of the valley, panning the soil until it likewise becomes barren. Excavation at this point should uncover the "mother lode."

Obviously the same rules of rock association apply to lode deposits as to placer deposits. Some metals, such as gold, tin, and nickel, have the habit of occurring only in certain types of rocks. For example, to prospect intelligently for nickel ore, one would first find areas in which certain dark-colored basic intrusives occur and then make a detailed search in those particular areas. Here the geologic map becomes of great importance, for the geologist with such maps available can determine in advance exactly where the sought-for associated rock is found and confine his field search to those areas.

In addition to the type of rock, the environment also is of great practical importance. For example, some deposits are naturally confined to zones where an igneous intrusion borders rock receptive to the passage of mineral-bearing solutions escaping from the magma at the time of the intrusion. Some rocks, such as limestone, are more susceptible than others to mineralization along contacts. If the geologic map shows an igneous intrusion in contact with limestone, the contact zone is a good place to search for ore deposits.

By no means all ore deposits are confined to igneous rocks. In many places the ore-bearing solutions have penetrated sufficiently far out from the source magma that they have entered sedimentary rocks. Here again the susceptibility to the passage of solutions and the precipitation of minerals varies widely. In some districts a limestone or sandstone of a certain age carries the greater part of the ore; the scientific prospector diligently searches for this particular formation in other areas.

Even where a mineral deposit does not contain minerals that resist the forces of decay and therefore occur in placer deposits, the minerals may have other properties which aid in their discovery. For example, pyrite (iron-sulphide), which is an abundant gangue mineral in hydrothermal veins, oxidizes to a yellowish-brown hydrous iron oxide known as limonite. This mineral so impregnates the vein at the outcrop that it may be possible to recognize it from distant points, and even in air photographs. The limonite capping of a vein is called *gossan,* or "blossom." Under favorable conditions minerals other than pyrite also produce a characteristic blossom at the outcrop. Copper minerals are transformed to the readily recognized green copper carbonate if carbon dioxide is available. Lead, zinc, and other metals likewise have characteristic, but in most cases less brilliantly colored, oxidization products. However, in a great many instances percolating water has leached away all the metalliferous minerals in the outcrop zone except limonite. Knowing this, prospectors have sunk shafts into countless limonite gossans in the hope of finding valuable minerals below the oxidized section of the vein. Unfortunately, many veins consist only of pyrite, quartz, and other valueless minerals, so that a great amount of time and money has been wasted in futile exploration. An investigation was conducted by geologists a few years ago for the purpose of determining if criteria could be found in gossans which would be indicative of the preoxidization presence or absence of ore minerals. The investigation was successful, and a set of criteria was developed by means of which a minute examination of the material composing a gossan enables a geologist to predict the nature of the minerals occurring in the unoxidized vein below the gossan.

Another guide to ore is based upon knowledge of mineral associations. Many veins consist solely of gangue minerals. Such veins have been opened by optimistic miners who hoped that they would encounter pay ore. The study of mineral associations has determined that some gangue minerals are most likely to be associated with ore minerals, while other gangue minerals are practically never found with minerals of value.

Fig. 184. Placer gold miner with his gold pan. Within pan is his entire season's harvest—about $1500 worth of gold nuggets and "dust." Cottonwood Creek, Alaska. *By Alex Liska.*

The ore-bearing solutions, in their travels outward from the source, are controlled by the structure of the rock. If the channelways originally lay in a permeable, sedimentary rock formation, then the ore-bearing solutions were confined to that rock and the ore will be concentrated where structural conditions, such as an upfold or anticline, caused a damming of the flow so that precipitation took place. The channelway may also have been a fault; in fact many great ore deposits occupy faults, so that they can be traced by geologic mapping of the fault itself. In other cases, where the ore-depositing solutions followed joint cracks, a study of the fracture system of the rocks aids in ore discovery.

Prospecting instruments. The most famous of all prospecting instruments is the miner's pan (Fig. 184). The prospector shovels stream gravel, or loose rock detritus, into the pan and then adds water. The pan is tilted and agitated so that the heavier mineral grains, such as magnetite ("black sand") and gold work toward the bottom, and the quartz and other lighter constituents work to the top and spill out over the lip. Quickly with skillful panning, only the very heaviest mineral grains (in the case of gold the gold "dust") remain in the pan to give a clue as to the value of the deposit.

The great deposits of residual iron ore in the western Great Lakes district have been thoroughly prospected by another method. Because of the slight relief and a cover of soil, glacial drift, swamp, and vegetation, these deposits are very poorly exposed. However, certain iron oxides will attract a compass needle or other magnet. By utilizing this property, geologists have discovered and mapped the outlines of deposits of magnetic iron-ore both in the Great Lakes district and in other parts of the world. The dip needle compass, the needle of which swings through a vertical arc, has been extensively employed for this work, as well as the usual type of compass. The position taken by the compass needle, whether swinging in a horizontal or vertical plane, in regions underlain by iron ore, is always the resultant of the attraction of the hidden ore body and the magnetic field of the earth. A more delicate instrument for measuring the magnetic properties of rocks is the magnetometer, a device that has been used not only for discovering rocks of high magnetic intensity, but also buried iron pipes and explosive mines. One development of World War II was the air borne magnetometer, by means of which the airplane became an effective discoverer of lurking submarines. It is expected that the airborne magnetometer will also have a peaceful role in the discovery of hitherto unknown deposits of valuable minerals.

Some progress has been made in recent years in the use of electrical instruments to determine the possible presence of buried ore deposits. This method is based on the lower electrical resistivity of sulphide ore minerals and of water-saturated zones of hydrothermal alteration. It is becoming an increasingly important method of prospecting.

Some ore minerals possess certain properties that can be detected by special instruments. For example, scheelite, a valuable ore of tungsten, is fluorescent, so the modern method of scheelite prospecting is with a portable ultra-violet lamp. When used in the dark, the ultra-violet rays produce a distinctive glow from grains of scheelite buried in the rock. In a similar manner, a portable Geiger counter has been devised to inform the prospector when he is in the vicinity of radioactive ore minerals.

Mining geology. The usual miner's rule to "follow the ore wherever it goes," although valuable, is not sufficient in modern practice. The "pay" ore may dwindle and even disappear during the following of a vein. However, the profit-paying minerals may reappear elsewhere in the vein where local geological conditions were more favorable to their deposition. Following the old rule, the miner might cease operating and perhaps miss an opportunity to find more ore, or he might continue to extend his mine workings without return, acting merely upon hope. "Dead work" (tunnels and shafts excavated in barren rock) is extremely expensive and should be paid for out of past or future profits. The application of geology to the mining of ore deposits not only has led to the discovery of additional deposits, but also has lessened to a considerable extent the amount of "dead work" done.

The use of geology data and research by the mining industry in the United States began with the publication, in the 1880's and 1890's, of a series of monographs on such mining districts as Leadville in Colorado and Comstock in Nevada written by able geologists on the staff of the U. S. Geological Survey. These publications were of great help to the mine operators in solving their problems and in searching for new ore bodies. The first mining company geological staff was formed at Butte, Montana, in 1900. Now most of the larger companies throughout the world have such staffs.

The duties of company geologists are many. One of the most important is the preparation of geologic maps. These include both maps of the formations that outcrop at the surface and maps made from observations and core drilling in the mine workings underground. The surface and underground maps in combination give a three dimensional picture of the geology. Rock formations and distinctive types of hydrothermal alteration are mapped wherever exposed, and the position of the rocks between exposures is interpolated. The mere recognition of some of these formations may be difficult, requiring not only a trained geologist, but also the use of a microscope. Maps made by the geological staff of a mining company include, in addition to geological formations and boundaries, the structural geology, such as the attitude of the rocks at all points, faults, and fractures, the position and thickness of veins, and the zones where the wall rocks are altered or brecciated. The staff may also map the surface topography, especially if the relief is great, because of the possible relationship between some of the features observed underground and the topography and drainage at the surface.

Predictions can be made from these maps as to the presence or absence of ore in places not yet penetrated by the mine workings. Some of the results which have been obtained through the making and utilization of geological maps and from allied information acquired by geological staffs are mentioned briefly in the following paragraphs.

(1) Maps give evidence as to the kind of channelways used by the ore-depositing solutions. This information is important, assisting not only in following the known veins, but also in the search for hitherto undiscovered veins.

(2) The structural and chemical conditions that caused the ore minerals to be deposited may become evident through study of the maps. Other places may be found where a similar environment existed.

(3) Detailed geological maps of ore deposits make possible recognition of any relationship that may exist between the location of the ore bodies and the structure of the containing rocks. For example, the ore minerals have been deposited in fractures, and the structure map shows the fracture pattern or trends through the country rock. Two different sets of parallel vertical fractures are present in many mining districts. In some localities the veins occupy one set only, and in other places both sets of fractures have been loci of ore deposition. In the latter case the fracture intersections become extremely important because there the veins will be largest and perhaps richest. The extension of the directions of fracture into as yet unprospected parts of the country rock may suggest other places where ore bodies are likely to occur.

Ore deposition took place in some districts in cracks created by earlier fault movements. Detailed geological mapping may result in the discovery of other pre-ore faults which likewise may be ore-bearing. Where the country rock is stratified and folded, the ore minerals, just as oil and gas, tend to concentrate in anticlines. Structural mapping determines both the location and magnitude of these folds.

(4) Geologic mapping brings about recognition of the effect of wall rock on ore deposition. If the map shows that the vein thickens

or its value increases where it passes through a particular type of rock, the map may also show places not yet reached by mine operations where this same or similar rock is intersected by the vein. Also some veins have a tendency to branch out along bedding planes in the wall rock, and the geological maps may show other places where such conditions are likely to occur.

(5) Certain types of rock alteration or the presence of brecciated zones in the rock may signify that ore is nearby. Mapping these features may lead to the discovery of hitherto unsuspected ore bodies.

(6) A detailed study makes possible the determination of the geological history of a region, especially the relative age of the vein in respect both to the rocks and to periods of diastrophism. As a result, the formations that are younger than the veins can be recognized. Naturally, prospecting in these formations would be futile. Post-ore deformation, especially faulting, will, of course, change the position of a vein. By means of a detailed geologic map, both the direction and magnitude of movement can be determined, and the geologist will be able to advise the mine operator as to the shortest route to the displaced section of the vein.

(7) The geological map also shows the depth of the zone of enrichment. If the mine is operating entirely upon enriched ore, the geological staff by means of microscopic studies of ore specimens may be able to forecast the character of the underlying primary ore body.

(8) By means of assay records entered upon the map, the persistence of the valuable minerals with depth can be estimated. If there is a steady decrease in value, it is possible to compute at approximately what level the increased mining costs and decreased returns will strike a balance forcing the mine to cease operating.

The geologist is of considerable practical value to his company because of his ability to identify minerals, both in the hand specimen and under the microscope. Several cases are on record of failure, before the days of mining geologists, to recognize valuable minerals in ore deposits. The silver-bearing lead carbonate ores of Leadville and the gold tellurides at Cripple Creek were at first unrecognized and discarded. Changes in mineral content and texture from one part of a vein to another are noted through microscopic examination of polished surfaces of ore specimens. These changes may be of utmost importance as criteria of the character of the vein beyond the present limits of mining operations.

The engineering staff likewise benefits from the geologic maps. Openings may exist in certain rock zones that would cause drainage of large quantities of surface water into the mine, with consequent increased pumping costs. These permeable zones will be shown on the geologic maps, and forewarning may permit avoidance during mine development work. In addition, the maps may show the presence of zones of crushed rock in which tunneling would be both difficult and expensive.

The explorations of ore bodies by diamond drills should be done under the supervision of the geological staff, who will first determine the location and direction of the drill holes and then study and report on the cylindrical cores obtained during the drilling operation.

The core drill is a very useful tool of both the geologist and the engineer. It is so named because it produces a solid cylindrical "core" of the rock penetrated. From the core, information can be obtained concerning not only the composition of the rock, but also its texture and structural relationships. The diameter of the core (and of the drill hole) depends upon the equipment used. Sizes range from less than an inch to three feet. Drilling holes with a diameter of five feet is a relatively new development; its advantage lies in the opportunity given to lower a man bodily down the hole where he can observe even more regarding the rock than is possible with the core.

The sampling of the ore preparatory to assaying is in charge of the geological staff in some companies. Geologists may be called upon to estimate the reserves of ore in a mine and to make appraisals. Boundary suits based on the "apex" law, which states that the locator of a vein possesses title to the vein from its high point, or apex, down the dip as far as it goes, has led to a great deal of litigation in which geologists testify as expert witnesses.

PROSPECTING FOR MINERAL DEPOSITS IN METAMORPHIC ROCKS

The search for mineral deposits characteristically occurring in metamorphic rocks demands first a hunt for the particular type of rock in whch the desired minerals are most likely to occur. For example, one type of asbestos is found only in serpentine, a green metamorphic rock, the origin of which was described in Chapter 11. Serpentine asbestos is mined in the province of Quebec, and elsewhere. A nickel-bearing mineral, known as garnierite, occurs in serpetine in New Caledonia. In this case the rock from which the serpentine was derived was a nickel-bearing igneous rock. The minerals magnesite, talc, and soapstone are found in magnesium-rich metamorphic rocks. Deposits occur in California, Virginia, and elsewhere where this particular type of metamorphic rock exists.

The sillimanite group of minerals used in making refractory porcelain for spark plugs and laboratory ware occurs in metamorphic rocks which are unusually rich in aluminum. Such rocks occur in the Inyo Mountains of California, in the southern Appalachians, and in several foreign localities. Graphite occurs in metamorphic rocks where the original rock was a carbonaceous sediment. Extreme metamorphism changed the organic material into flakes of graphite. Garnet, which is used mainly as an abrasive, occurs in commercial quantities only in schists.

The general localities where these various metamorphic rocks are abundant are already known. The prospector looking for a particular mineral confines his search to belts of favorable rocks. This procedure was followed with marked success in the case of the sillimanite minerals. About thirty years ago, laboratory investigations discovered that these minerals could be converted into a spark-plug porcelain far more durable than any in use at that time. However, no commercial deposits of the sillimanite minerals were available. But it was known that the Inyo Mountains of California contain large masses of aluminum-rich metamorphic rocks. These were prospected with great care, and after months of search large deposits were discovered which are now being exploited.

PROSPECTING FOR COAL AND OTHER BEDDED ROCKS

Coal is a sedimentary rock occurring in beds which lie parallel to the overlying and underlying strata (Figs. 111 and 134). However, beds of coal may not be as consistent in thickness as the other sedimentary rocks in the section, perhaps thinning down in places so as to be not workable, or even disappearing entirely. The original swamp in which the coal was deposited, although possibly covering hundreds of square miles, nevertheless had very definite boundaries, and coal would not be expected beyond the swamp borders.

Coal may be folded into anticlines and synclines, and it may be faulted. Except in the arid southwest where steep slopes barren of vegetation occur, coal does not ordinarily outcrop because it is relatively soft and slumps readily, so that it becomes covered with soil and loose rock and further obscured by vegetation. Many coal beds have been discovered through the digging of water wells, basements, and road and railroad cuts.

Geologists can determine the stratigraphic position of a coal bed and then pick up the bed in places perhaps many miles away, where its presence had not heretofore been suspected. The first step is to see where the coal lies with respect to sedimentary formations, above and below, which are well exposed and can be recognized at the outcrop. To do this the geologist measures the vertical section of the rocks in a district, including whatever coal beds may be present. The next step is to map the surface geology and obtain elevations of outcropping formations at various points. With these data, a structural map can be drawn which will show the regional dip, anticlines, synclines, and faults. By using the outcrop and structural maps in conjunction, a geologist can detect almost at a glance the areas that are underlain by coal and the areas from which the coal has been removed by erosion. Furthermore, with the aid of a topographic map, which gives the elevation of the surface, it is possible to determine the depth to coal at any point. Places where the coal would outcrop were it not for a thin soil cover become apparent in this way, and test pits are dug at the geologist's direction so that coal samples may be obtained and the thickness of the seam measured. If the coal is too deep to allow digging of test pits, the best procedure is to core-drill the rocks at regular intervals, in order that the coal may be sampled and the thickness of the seam noted.

The samples obtained at the test pits or by core-drilling are analyzed to make sure that the coal continues to be of commercial grade. Then, from the accumulated data, the geologist prepares a map which shows the thickness, quality, and depth of the coal at all points. Such a map is of invaluable aid to the operator, for it gives him the tonnage and availability of his coal, as well as information with which exploitation can be directed.

Coal-bearing rocks that are faulted may cause trouble in mining because the seam is likely to end suddenly, leaving the miner at a loss whether to go up, down, right, left, or straight ahead in order to regain the seam. The geologist, through studies at the surface and in the mine, should be able to tell the operator the direction and magnitude of the movement, so that the coal across the fault can be picked up again with a minimum of time, labor, and expense.

The same general routine followed in prospecting for coal is used in the search for all other bedded deposits. Examples of non-metallic mineral deposits which occur in sedimentary beds are limestone, clay, rock phosphate, salt, and gypsum. In addition, a few metalliferous deposits have a similar environment. Some iron ores, including the Clinton (Silurian) hematite deposits of the Appalachian province, are of sedimentary origin and occur in beds, as do sandstone, shale, and coal. Other metallic deposits are not in themselves sedimentary in origin, but are confined to certain layers in bedded rocks. For example, some of the native copper mined on the Michigan Peninsula was deposited in conglomerates, the ore-bearing solutions using the pores between the grains and pebbles as channelways. The great gold deposits of the Rand district in South Africa likewise occur in a bed of conglomerate, but geologists are in disagreement as to whether this gold was originally in the gravel as a beach placer or whether the gold was introduced subsequently as was the copper of the Lake Superior district. However, regardless of origin, both the copper and the gold occur in sedimentary beds, and consequently, the ore bodies conform to the rock structure.

THE SCIENCE OF OIL-FINDING

Formerly entirely a matter of chance, the search for oil and gas in more recent years has become a science. Chance has not been completely eliminated, and probably never will be, for many wells favorably located from a geological standpoint prove to be failures. However, the use of scientific method has brought about the discovery of hundreds of new pools in the last few years, while those who drill without benefit of geological information discover a smaller proportion of the new pools each year. In fairness to the "unscientific method," however, it must be stated that the discovery of the great East Texas field was not due to recommendation by geologists, but was a magnificent piece of luck.

Today all of the larger oil companies have geologic staffs. The petroleum geologist has made his profession indispensable to the oil industry. Recognition of the value of geology in the search for mineral wealth is greater in the case of oil and gas than in that of any other mineral resource.

Methods in the search for petroleum can be classified into two types: surface and subsurface. In the former case, the geologist draws all the conclusions possible from observations made in the field while traversing an area. Subsurface geology involves study of the buried rocks by means either of well logs, cores, and cuttings obtained from wells drilled in an area, or of records made by geophysical instruments (to be described later) which, though set up on the surface, obtain a record of the rocks at depth.

For many years the emphasis in petroleum exploration was on surface geology. Now, however, so much of the surface where the rocks are exposed and are favorable to the occurrence of oil has been studied and mapped that most areas undergoing investigation are those in which surface methods are impossible and subsurface methods must be employed.

The geologist assigned to surface study of the oil possibilities of a region covers his area with great care. He travels by whatever means the country affords, using automobile, horse, and boat where possible. Much of the area is covered on foot; in some cases the entire work must be done in this way. Valuable geological information can be obtained in some regions by photographs taken from an airplane.

One of the things looked for by the field geologist is any surface indication of oil or gas. Oil may seep to the surface, forming a spring, or, as is more often the case, it is brought to the surface by water on which it makes a readily identifiable film. Oil at the surface tends to thicken into asphalt due to the escape of its more volatile constituents. Gas seeping to the surface may either emerge from the rock with a hissing sound or it may bubble up through mud, creating what is known as a *mud volcano*. Oil and gas seeps, however, are not necessary to the presence of oil at depth. In fact, seeps are unknown in the neighborhood of most of the great oil and gas fields of the Mid-Continent region. The mere presence of a seep is indication that the hydrocarbons have opportunity to escape, a condition which does not make for accumulation in great quantity. But where the strata are very much contorted and faulted, the reservoir rock that is cut by a fissure at one point which permits the escape of oil may, a very short distance away, be folded into a perfect trap from which there has been no escape. This is the condition in California and in many of the foreign fields where oil seeps and asphalt lakes are fairly common. In the Mid-Continent, the strata as a usual rule have a very gentle dip and the oil and gas occur in structural traps which lie many miles from the point where the reservoir rocks crop out and where the few seeps found in that region occur.

In addition to looking for possible surface indications, the petroleum geologist while traversing an area records the following pertinent observations:

(1) The presence or absence of sedimentary rock. Oil accumulates in commercial amounts only in sedimentary rocks (with in-

significant exceptions), so that those parts of an area that are underlain by igneous and metamorphic rocks can be ruled out as possible oil territory.

(2) The presence of possible source rocks. These are carbonaceous rocks or organic limestones which were deposited in marine waters fairly close to shore. Where possible source rocks are absent, the chances for oil are less.

(3) The presence of possible reservoir rocks. If the rocks within drillable depths do not contain pervious beds there will be no place in which oil can be stored. The age of potential reservoir rocks is also important, because if they are the same age as formations which contain commercial quantities of oil elsewhere, they give greater promise than if they were non-productive in other fields.

(4) Whether possible reservoir rocks are overlain by impervious strata (cap rocks); otherwise oil and gas will have had opportunity to escape.

(5) Whether the thickness of the sedimentary series is adequate to make exploration justifiable. In some areas the pre-Cambrian "basement" rocks are covered by but a few hundred feet of sediment. It would obviously be a mistake to recommend testing such a thin section of strata.

(6) If the rocks are severely folded, whether they have been so squeezed and heated during diastrophism that any oil originally present has been destroyed. By analytical methods in the laboratory, the degree of metamorphism of coal or any other carbonaceous rock in a district can be determined, and from this figure it is possible to make a fairly definite conclusion as to whether petroleum, which is a relatively vulnerable substance, can have survived.

(7) The sedimentary rock section should be examined and measured in detail in order that (a) irregularities including angular unconformities and variations in thickness of different units may be noted, (b) the presence may be discovered of soluble rocks that might be dissolved in some places so that the overlying rocks have slumped, and (c) the geologist may be able to map the outcropping formations.

Finally, by means of instruments, the field geologist maps the structure, or inclination, of the sedimentary rocks. The structure map shows the location of the synclines, anticlines and faults. These data, in conjunction with the measurements of the stratigraphic section, make possible the determination of the depths to possible reservoir rocks in any part of the area. The field maps also yield information as to the size of the area supplying the oil which has migrated up-dip until caught in an anticline or other trap. The larger the "gathering" area, the greater will be the amount of oil stored in a pool, provided that other factors are equal. Faults, if present, are mapped in detail and observations taken as to whether such faulting may have had any possible effect on the retention or escape of oil or gas.

With all these data available the geologist is in a position either to condemn an area as lacking oil and gas possibilities or to recommend that it be tested. In the latter case he gives the location of the most favorable place in the district and recommends that the first test be drilled there. Economic factors, of course, also enter into the picture. The cost of drilling and the availability of market must be taken into account, as well as geological conditions.

Great evolution has taken place in the last few years in subsurface methods of petroleum geology. When a well is drilled for oil, gas, or water, the driller makes a log of the different formations and their depths as they are passed through by the drill. He may also take and save the *core* of the hole if his drilling equipment is of the type that makes this possible, or he may save the rock fragments or *cuttings* produced by the drill. Needless to say, the records of deep wells, whether or not the wells are successful in their quest, are of great value. The structure of a deeply buried formation may be mapped over a wide area by means of these records. Subsurface structure maps have been made of most oil fields and of many areas thus far nonproductive.

The discovery of the greatest of all oil fields, in eastern Texas in 1930, focused attention on the so-called "stratigraphic trap." There, Cretaceous sandstone of wide distribution pinches out on the side of a large structural dome, the highest point of which is in northwestern Louisiana. Oil moving up the dip of this highly permeable sandstone from a basin in northeastern Texas has been effectively trapped by its pinching out. In other fields oil has been trapped by the up-dip disappearance of permeability, or by damming where an inclined permeable layer is covered by an impervious layer at an unconformity. None of these oil traps can be discovered by surface observation, but evidence of their existence can be obtained from subsurface records. This method of exploration for new oil pools will in all probability be even more effective in the future than it is at present.

Where the bed rock is obscured by deposits of sand, gravel, glacial drift, and other types of mantle rock, oil companies may map the structure of the buried formations by using a core drill. This drill is set up at definite intervals, and a hole is drilled down to some recognizable bed-rock formation. By measurement of the depth of the formation and determination of the surface elevation at the drill-site, the elevation of the buried formations can be obtained at every point drilled. Then the construction of a contour map showing the structure of the buried rocks is a simple task.

Geophysical instruments are so named because they apply certain laws of physics in a study of the earth's crust. The three most common geophysical devices used in petroleum exploration are the gravimeter, seismograph, and magnetometer. These machines are based upon different physical laws and consequently have no resemblance to each other. The gravimeter depends upon differences in the pull of gravity at different places. For many centuries physicists have realized that a plumb bob or a pendulum is deflected from the vertical when set up close to mountainous regions. This deflection is due to the fact that the great mass of the mountains exercises gravitative attraction upon the plumb bob or pendulum. Similarly, where rocks of abnormal specific gravity (density) occur beneath the surface, their presence can be determined by gravity instruments.

The seismograph is an earthquake-recording machine. Elastic waves caused by an earthquake travel through the rocks and reach seismographs set up on the surface at different times, the length of time depending upon the distance traveled and the elasticity of the rocks encountered. In petroleum exploration, an artificial "earthquake" is produced by exploding dynamite at the surface, and records of the shock are obtained by several conveniently located seismographs. The waves produced by the explosion travel down toward the center of the earth, but formation boundaries, where rocks of quite different character, such as shale and limestone, make contact, reflect some of the waves back to the surface. By means of *seismograms* (the records obtained by seismographs), it is possible to calculate the distances downward to the different reflecting surfaces so that the structure of the buried rocks can be mapped. The seismograph has been successfully used in discovering such buried features as salt plugs, mountain ranges, and anticlines.

The accompanying cross-section illustration (Fig. 185) shows how an anticline can be discovered and its outlines mapped by means of the reflection seismograph. Many oil pools have been discovered in recent years by this procedure. The explosion set off near the shooting truck creates an artificial earthquake. Some of the waves from this quake are reflected back to the surface by the tops of the relatively hard limestones. These waves make records upon their arrival at the various receivers which are connected with the recording truck. The seismogram recorded at each station shows the time of the explosion, and the time of the arrival of the reflected waves. Obviously if the time interval between the explosion and the arrival of the reflected waves is shorter at station *A* than at station *B* the buried formation rises between *B* and *A*. As a matter of fact, by applying earthquake-wave velocity formulae, it is possible to calculate the depth of the reflecting rock at every point lying between the explosion point and each seismograph station. By determining surface elevations with surveying instruments, the elevations of the points on the buried rock formation can be calculated. By systematically covering an area with explosion points and seismograph stations, it is possible to obtain sufficient subsurface elevation data to permit the construction of a *structure con-*

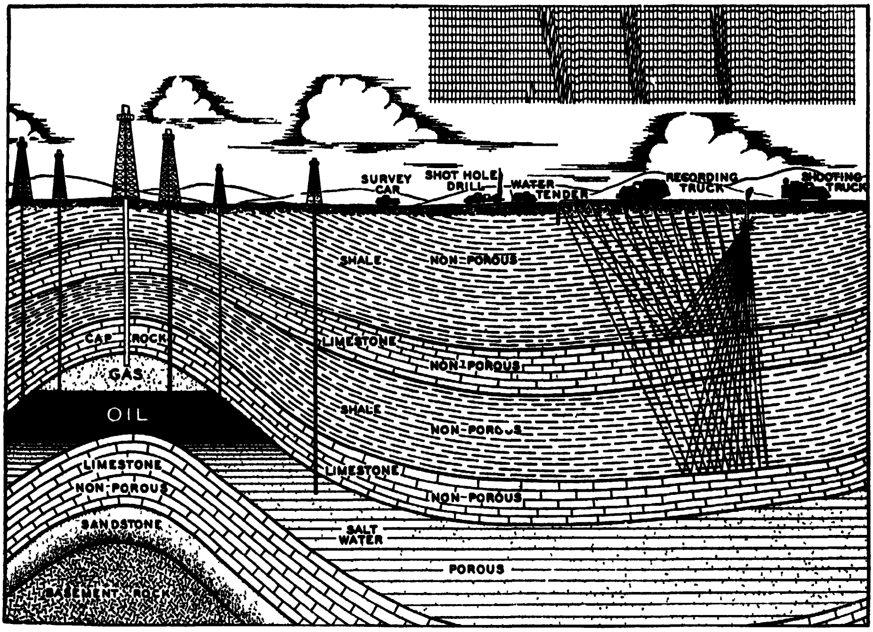

Fig. 185. The seismic method of prospecting for structures favorable to the accumulation of oil or gas. To the left of the "shooting truck" an artificial earthquake has been created by detonating a charge of explosives set in the bottom of the "shot hole". Some of the waves created by the shock are reflected upward by the more rigid rock layers. From the time which it takes a wave to travel from explosion to reflecting stratum to recorder, the depth to the bed rock stratum can be determined for each recorder point. From these data and surface elevations the bedrock elevations can be obtained and the presence or absence of anticlines or other structural rock "traps" determined. Seismograms shown at upper right. *Courtesy Seismograph Service.*

tour map. The latter will show the configuration of the buried rock formation in the same way that contours are used to show the configuration or topography at the earth's surface. Where such maps prove the existence of domes or anticlines, these are tested for oil by a drilled well.

A less used method is the *refraction* method of prospecting with a seismograph. In this case the interpreter uses the record of waves which have been refracted (bent) upon entering the formation being mapped, and which return to the surface at a considerably greater distance from the shot point than do the waves which are reflected off the upper boundary of the buried formation.

Magnetometers measure variations in the magnetic attraction of buried rocks. Theoretically the rise and fall of a layer of magnetic rock, such as a sandstone containing abundant magnetite, would produce varying magnetic intensities at the surface. However, magnetometer records are not as easy to interpret geologically as are those of the seismograph and gravimeter. Therefore this instrument, although much cheaper to operate, has not had the success of the other two.

Considerable experimentation has been carried on in recent years with electrical instruments. Some have been useful in discovering certain types of ore deposits and in finding shallow bodies of ground water, but so far they have not proven consistently successful in mapping the structure of deeply buried rocks.

Many fields of the Gulf Coast and Mid-Continent regions have been discovered during the last five years by the use of geophysical instruments. In fact, more salt domes have been discovered by the seismograph and gravimeter than were known to exist before the advent of geophysical instruments. Up to the present time, no device has been invented that will determine the actual presence or absence of oil. All of the accepted instruments now in use are confined in their scope to the discovery of rock structures favorable to the accumulation of oil. Many devices have been put forward as capable of detecting oil, but none as yet has proved to be successful. The nearest approach has been a method known as *soil analysis.* This method is based on the assumptions (1) that no rock is completely impervious, so the lightest hydrocarbons have been able to escape from an oil deposit to the surface, and (2) that as these hydrocarbons passed through the soil at the surface traces adhered which can be determined by microchemical analysis. Although this method has not lived up to early expectations as yet, it is still possible that greater refinement of analytical procedures may make its use feasible.

Instruments which their inventors claim will detect buried oil pools are known as "doodle-bugs" by men in the petroleum industry. The "doodle-bug" is the modern descendant of the divining rod used throughout historic time by persons with alleged mystical powers for locating minerals, water, and buried treasure, and for detecting criminals.[1]

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[1] Although discredited by the U. S. Geological Survey and other authorities, the divining rod continues to be a subject of considerable popular interest. An extensive history of the use of the divining rod and a lengthy bibliography on the subject are given in: Ellis, Arthur J., The Divining Rod, a History of Water Witching. U. S. Geol. Survey, Water Supply Paper 416, 1917.

tour map. The latter will show the configuration of the buried rock formation in the same way that contours are used to show the configuration or topography at the earth's surface. Where such maps prove the existence of domes or anticlines, these are tested for oil by a drilled well.

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CHAPTER 18

Geology in Engineering Projects

SOME OF THE METHODS USED IN THE attempt to control destructive geologic forces, such as those causing soil erosion and disastrous floods, were described in various chapters in Part Two. The methods employed to combat these forces are essentially those of the engineer. This chapter describes how the methods and knowledge of the geologist are utilized to solve some of the problems encountered in engineering construction. One function of the geologist is the locating of adequate supplies of needed rock materials. Another direction of activity is created by the ability of the geologist to appraise the suitability of a site for reservoir, dam, bridge, tunnel, or other engineering structure.

The last few years have seen great expansion in large-scale engineering construction. This growth has been accompanied by a growth in the profession of engineering geology, which covers the application of geology to engineering problems. As a result, both money and lives have been saved. Engineering history is marked by failures of dams and other structures; in most cases these catastrophes were due not to erroneous calculation of strength and design of structures, but to failure of the rock in the foundation, the inherent weaknesses of which were not appreciated because no adequate investigation had been made by an engineering geologist. It is, of course, absurd to place a mass of reinforced concrete of much more than adequate strength upon a natural rock foundation too weak to hold it; yet this has been done many times in the past.

Materials surveys. Many engineering projects require natural materials, such as stone and sand, which are obtained locally. The duty of a geologist employed on such projects is to locate deposits of the needed materials as near-by as possible, so as to avoid unnecessary transportation costs. The geologist must also make certain that all rock materials used are of proper quality, adding testing techniques of his own, such as microscopic investigation, to those already employed by the engineering staff.

Materials surveys are needed where highways are being surfaced, where the banks of streams are being protected by riprap, and where dams, aqueducts, breakwaters, jetties, and other large structures are being erected (Fig. 186).

Riprap is the material used to prevent lateral erosion of river banks, especially on the outside of meanders. If stone is used for this purpose, not only must the geologist find adequate supplies as close as possible to the project, but he must also ascertain that the stone used is insoluble, resistant to abrasion by running water, and resistant to decomposition through atmospheric attack during low-water stages. The joints and other planes of easy fracture must be spaced far

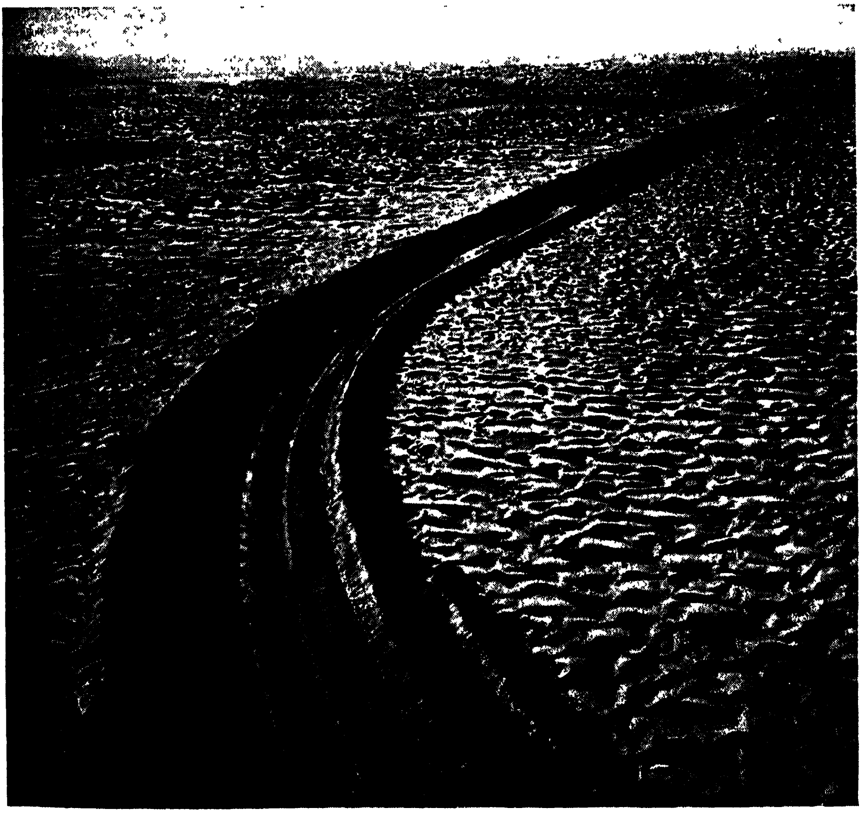

Fig. 186. Aqueduct—the All American Canal in sand dune area near Yuma, Arizona. ***By permission Spence Air Photos.***

enough apart so that blocks too large to be moved by river currents, even in times of flood, can be obtained. Likewise, the stone used in the construction of breakwaters and jetties must be of a type which will withstand the various agents of destruction to which it will be exposed.

A large market for rock material is in concrete aggregate, used in the construction of buildings and various engineering structures, and for road surfacing. An essential constituent of concrete aggregate is sand, which may be found in the beds and flood plains of modern streams, or in terrace deposits which are flood plains of ancient streams. Other favorable localities for sand are delta deposits which were formed in temporary lakes that fringed the great continental glaciers of the past, dune areas (although in many cases dune sand is too fine for use in concrete aggregate), and ocean and lake beaches. An equally essential constituent of concrete is the coarse aggregate, which may be either gravel or crushed stone. The search for gravel covers the same ground as the search for sand, except that windblown sediment is rarely, if ever, sufficiently coarse to be classified as gravel. If crushed stone is used, the rock must meet rigid specifications as to hardness and durability. Organic material, clays (which swell on contact with water), and rock liable to disintegration because of cleavage, porosity, or other property must be avoided. Locally obtained volcanic ash, or pulverized volcanic tuff, has been added to the ingredients in making concrete in some construction projects, notably the Los Angeles aqueduct.

Rock materials are used also in the construction of asphaltic roads. In one type of road, liquid asphalt is obtained either from petroleum refineries, where it is a byproduct, or imported from a large natural asphalt deposit such as the one on the island of Trinidad in the British West Indies. This liquid asphalt is mixed with locally obtained sand and poured on the road being surfaced. A second type of asphalt road is made from a natural mixture of rock and asphalt occurring where petroleum seeping to the surface has impregnated the rock and soil and has become asphaltic due to the escape of the more volatile hydrocarbons. In this case the impregnated rock is crushed and rolled onto the highway surface. It is the cheaper method of asphalt road construction in regions where natural deposits can be found.

Many secondary roads are surfaced with neither concrete nor asphalt, but are covered with a veneer of loose material which in time packs into a fairly hard surface. Materials which may be used in this way include sand, gravel, and crushed rock. If rock is used, it must meet certain specifications for durability, and also it must so occur that it can be economically quarried. In a few places, notably along the Front Range of the Rocky Mountains, granite has decomposed into a loose granular aggregate that can be scooped up and used to surface roads, making an excellent secondary road surface.

Reinforced concrete has largely displaced dimension stone in the building of engineering structures. Where stone is desired for facing, it is necessary to find quarry sites in sandstone, limestone, or massive rock.

The availability of abundant supplies of water is a necessity in all large projects. Where a camp is built to house the workers, water of good quality must be secured to take care of human needs. If surface water of satisfactory quality is not available, a geological investigation of the ground water resources must be made.

Dam sites.[1] Building a dam involves more than merely pouring a lot of concrete or heaping up a pile of dirt. First the ability of the valley above the proposed dam site to retain water must be investigated, as is discussed in the next section. Next, the ability of the rock beneath and abutting the proposed dam to withstand the weight of the dam and at the same time prevent the passage of water must be determined. A large masonry dam has enormous weight. The water impounded above a dam likewise has great weight, which presses against both the dam and the underlying rock. The water near the bottom of a reservoir is under enormous pressure, which forces it into the smallest of openings. As a matter of fact, no rock or concrete is entirely impervious to water under great pressure, and some leakage beneath, around and through a dam is inevitable. However, the leaking water must be prevented from attaining any appreciable velocity or it will scour larger openings, and breaching of the dam will follow.

Physical tests of the foundation rock, including determination of permeability and crushing strength, are not sufficient. Water under enormous pressure forced through the pores of a rock over a period of years may produce physical effects and chemical reactions that cannot be forecast by laboratory testing. The abutting rock has to withstand radically changed geological conditions also. Not only is water forced into it under pressure, but also the water table may be raised to heights not reached heretofore, and this changed condition may materially alter the character of the rock.

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[1] During the preparation of this and the following section a series of papers in a symposium on "Geology and Engineering for Dams and Reservoirs," published by the American Institute of Mining and Metallurgical Engineers, in *Tech. Paper No. 215*, 1929, was freely drawn upon. The authors of these papers include C. P. Berkey, Kirk Bryan, O. E. Meinzer, Charles Terzaghi, G. H. Matthes, L. W. Fisher and R. D. Ohrenschall, C. K. Wentworth, L. C. Glenn, and H. T. Stearns.

A geologist called in to investigate and report upon a proposed dam site has three subjects to cover: the overburden, the foundation and abutment rock, and the reservoir (which will be discussed in a separate section). The study of the overburden (and of the bedrock) is usually aided by core drilling at many points across a valley. These drill holes determine the depth to bed rock, make possible the securing of samples of both overburden and bed rock, and enable the geologist to observe the character of the overburden before rendering a decision on the necessity for excavation.

For shallow testing, pits may be dug or holes driven by hand into the ground until rock is encountered. In the latter operation either a soil auger is rotated through the dirt, or a steel bar is driven downward.

It is the custom in younger valleys to remove the overburden completely and foot the dam on bed rock. Through physiographic studies, the geologist may be able to make fairly close estimates of the depth and character of the overburden without recourse to drilling. However, this method is hazardous, for in some instances the bedrock floor of a valley is further incised by an older channel, which increases both the volume of alluvium that must be removed and the size of the dam itself. In one case on record, a buried channel lay between two test borings only 50 feet apart, and its presence was not realized until the overburden had been removed down to the rock floor of the main valley. On large projects, such as Hoover Dam (Figs. 187 and 188), the valley floor is contoured by topographic surveys, and the underlying bed-rock floor is contoured by means of diamond-drill holes so that complete information as to the thickness and volume of the overburden is available before operations commence.

In the older and wider alluvial valleys, since it is impossible or impractical to excavate to bed rock, the dam is footed on alluvium. This calls for quite a different procedure, which will be described in a subsequent paragraph where permeable foundation rocks are discussed.

Not only must the foundation rock be able to bear the weight of

Fig. 187. Hoover Dam (formerly called Boulder Dam), upstream side. *By permission Spence Air Photos.*

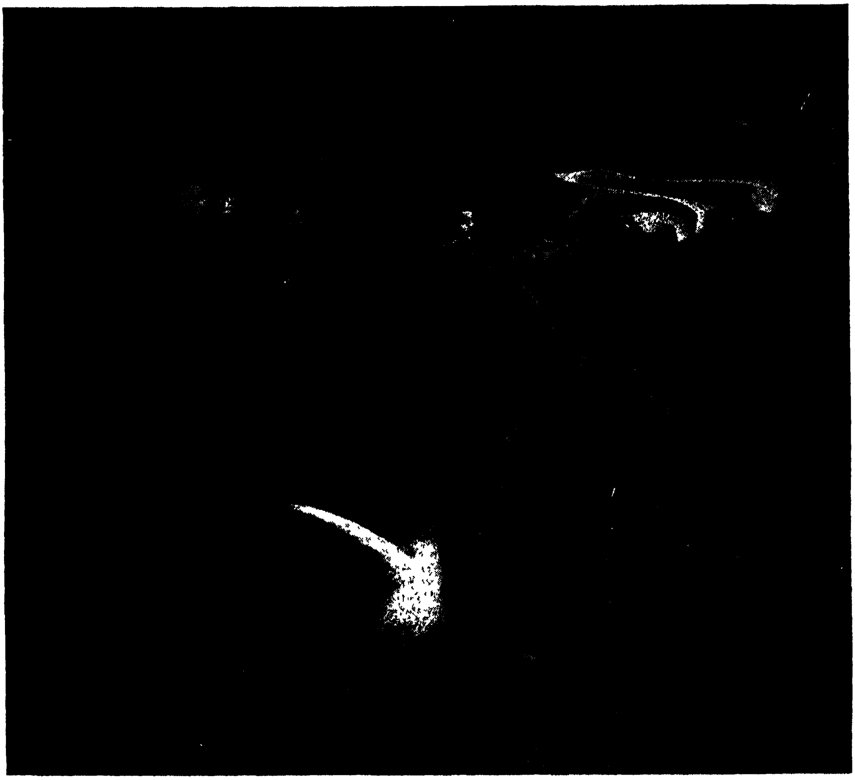

Fig. 188. Hoover Dam, downstream side. *By permission Spence Air Photos.*

the dam, but it must also resist the tendency of the dam to overturn due to the pressure of the impounded water. The competency of the rock to withstand these vertical and torsional forces must be judged. "A foundation may fail mechanically by being unable to withstand the thrust force, or tendency to slide or shear, exerted upon it by the pressure of the water behind the dam. If this pressure overcomes the frictional resistance offered by the foundation material, the dam will slide downstream. The slipping or shearing rarely occurs between the dam and the foundation, but is almost always a movement within the material of the foundation itself."[2]

However, more dam failures result from the escape of water through the rock beneath a dam than through sliding and shearing. Some seepage is to be expected, because even rocks that are otherwise fairly impervious contain fractures through which water can move. If the rock is composed of none but very insoluble minerals, these crevices do not enlarge and may even, in time, become smaller through gradual filling with silt carried by the seeping water. Cases are on record of silting up of rocks to such an extent that seepage noticeably decreased. However, if any soluble minerals are present, either in the rock or in the cement binding the grains together, seepage water widens the openings and the volume of escaping water steadily increases. If steps are not taken to remedy this condition, the seepage water will before long attain sufficient velocity to scour channelways, and disaster may follow.

Soluble rocks, inherently weak rocks, and permeable rocks give trouble when used for dam foundations. The soluble rocks include mainly limestone, dolomite, and gypsum. In such rocks not only do joints and fissures enlarge by solution, but the rocks may also be extremely cavernous initially. Impure limestones, however, are not as readily soluble and have been used successfully for dam footings in some instances. Sandstones and conglomerates in which the grains are held together by soluble cement, such as calcite or gypsum, tend to lose their cement and crumble when water under pressure is forced into the rock, no matter how impervious the rock may have been initially. The failure of the St. Francis dam in California was due to this condition.

The weak rocks include several different types. Shales and clays are variable in their reaction. Many soften when impregnated with water and become dangerously slippery. Fault gouge, finely crushed rock powder lying between the two walls of a fault, may act in similar fashion. Some basalts are so highly vesicular that they afford as many channelways for the movement of water as does a highly cavernous limestone. In addition, the polygonal vertical joints which produce a columnar structure in lava flows furnish further opportunity for water movement. Some schists have proven to be satisfactory foundation rocks, but, if partially decomposed, the altered, softer minerals make planes of weakness through the rock because they lie in schistose bands. Serpentine, a green altered igneous rock, is another inherently weak rock.

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[2] Glenn, L. C., *op. cit.*, p. 104.

A condition of weakness may exist also because "hard and soft materials, such as limestones or sandstones and shales or clays, are often interbedded in alternating layers and are likely to form a treacherous foundation, especially where the hard layers are the more prominent and the softer ones are either so thin as to appear negligible or, when freshly excavated, are so firm and hard as to appear perfectly safe. The softer layers may flow under the weight of the dam and cause a slight settling that would lead to the development of cracks and the failure of the dam .... The city reservoir at Nashville, Tennessee, failed some years ago because a portion settled slightly, cracking and slipping out by flowage and sliding on such a thin clay layer between harder limestone beds."[3]

Structural weaknesses of rocks include faults and shear zones. "Faults are often troublesome. In a region that is free from earthquakes further movement probably will not occur along old fault planes, but in earthquake regions such movement is not improbable, as witness the displacement for many miles along the San Andreas rift in the California earthquake of a few years ago. Even when there seems to be no danger of further movements, faults introduce planes of weakness in the rocks and provide seepage channels and permit upward pressure beneath the dam, all of which are undesirable and should be avoided if possible."[4] However, it has not always been possible in California to avoid faults in dam construction.[5]

Shear zones are masses of crushed rock resulting from earth movement. These zones may not be readily recognizable at the surface but may extend to great depth. The rock in shear zones is both structurally weak and vulnerable to the passage of water under pressure.

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[3] Glenn, L. C., *op. cit.*, pp. 103, 104.

[4] Glenn, L. C., *op. cit.*, pp. 109, 110.

[5] Louderback, George O., Characteristics of active faults in the central Coast Ranges of California, with application to the safety of dams: Bull. Seismological Soc. America, Vol. 27. No. 1, Berkeley, California. January, 1937, pp. 1-27.

Needless to say, high and heavy masonry dams are not knowingly built on weak or permeable rocks of the types just described. However, dams are built on alluvial deposits which are intrinsically permeable, composed of silt, sand, and even gravel. But the type of dam constructed is quite different from the type that can be footed directly on bed rock. Instead of concrete, earth is used, and the dam "must be a low one in order to keep down the pressure and consequent tendency to leakage, and the base of the dam must be extended far enough upstream and downstream that it, either alone or in connection with an apron or aprons, will so prolong the passage of water through the sands beneath the dam as to give a frictional resistance sufficiently high to prevent harmful seepage."[6]

The rock beneath the downstream side of a dam must be able to withstand the scouring effect of the water that flows over the dam or spillways. However, this erosion can be diminished by proper design of the dam and through the construction of a protective apron.

> At the dam across the Mississippi River at Keokuk, Iowa, the concrete apron at first provided to protect the horizontal, thin-bedded limestone below the toe of the dam from scour was found to be insufficient. In less than a year much of the limestone had been torn out and heaped in great piles somewhat lower downstream, so that additional protection became necessary. The failure of the dam at Austin, Texas was due to sliding on the foundation because the downstream toe was being undermined by erosion. . . . After sixteen months flow of the gates, the cherty limestone on which the Wilson dam at Muscle Shoals rests was undermined to a depth of 10 feet in places at the toe, and blocks of limestone weighing 200 tons were torn loose and piled up some distance below it.[7]

The rock walls at the sides of a valley into which a dam is tied are known as the abutments. They may be considered both part of the dam and part of the reservoir. Some leakage is to be expected around abutments, but if the percolation grows in volume remedial steps must be taken. The chances are that the abutment rock is more decomposed than the foundation rock because of greater exposure to the atmosphere. However, in the higher parts af the abutment, the pressures are not as severe, and the rock, even though weaker than it is beneath the dam, may be strong enough. The abutment rock should nevertheless be given just as close scrutiny and study as the foundation rock. Disasters have occurred through the failure of abutments.

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[6] Glenn, L. C., *op. cit.*, p. 106.

[7] Glenn, L. C., *op. cit.*, p. 105.

In order to emphasize not only the desirability but also the necessity for cooperation between geologists and engineers in the construction of dams, a few cases of dam failures and their causes are given in the following paragraphs.

Probably freshest in the public mind of the United States is the failure of the St. Francis dam in California on March 13, 1928. When this dam broke it allowed a great reservoir full of water to pour suddenly down a steep-walled valley to the sea, causing appalling loss of life and great property damage. The St. Francis reservoir was a part of the aqueduct system supplying water to the city of Los Angeles. Unfortunately, the construction of this dam was not preceded by a geological investigation or the dam would not have been built where it was. Following the disaster at least three geological investigations were made. About two-thirds of the dam was footed on mica schist and the balance upon a fresh-water conglomerate. The contact between the schist and conglomerate is a fault, but there is no evidence of any recent movement along this old fault plane which could have been the cause of the failure of the dam. A few paragraphs from a report made after the disaster follow:

> When dry, the conglomerate of the dam-site is fairly firm, although it is by no means a strong rock. A test, made for the State's investigating commission, gave a crushing strength of 500 pounds to the square inch, whereas the concrete of the dam has a strength of 2,000 pounds to the square inch. When wet, however, the rock shows a remarkable change. A piece about 2 inches in diameter taken from the northwest abutment of the dam at a point directly beneath the former structure, when placed in a beaker of water begins to flake and crumble and in about 15 minutes slumps to the bottom of the vessel as a loose gritty sediment that can be stirred about with the finger. Evidently the particles of the conglomerate are held together merely by films of clay and when the mass is wet practically all cohesion is lost. Even the fractured and faulted pebbles fall apart into small fragments.
>
> The conglomerate is traversed by many small veinlets of gypsum and it is probable that this mineral constitutes a part of the cement that holds the rock together when dry. The solubility of gypsum is well known, and the presence of this mineral probably contributes to the rapid disintegration of the mass when wet.

> Quite aside from any possibility of movement on the San Francisquito fault, it is plain that the dam, otherwise a well-designed and well-built structure, was planned without adequate knowledge of the geological features of the site and without proper consideration of the structure and materials of the rocks upon which it was to rest.
>
> It is probable that the dam failed initially at its northwestern end. As the conglomerate became water-soaked, the cementing clay and gypsum were softened and dissolved. The supposed rock upon which that part of the dam rested lost practically all of its strength and became no better suited for a foundation than a mass of wet earth or gritty clay. Seepage through this material probably increased rather suddenly to a jet of water which, rapidly attaining appalling proportions, washed out the softened conglomerate, permitting the concrete to crack and then to be swept out in huge blocks, up to 10,000 tons in weight, which were distributed for half a mile down the canyon. The terrific swirl of water about the toe of the dam undercut the layers of schist at the southeast abutment and probably within a few minutes of the opening of the first breach, the entire southeastern end of the dam slid down into the canyon, the largest fragment coming to rest against the toe of the standing middle segment.[8]

A concrete dam built across the Elwha River on the Olympic peninsula in the state of Washington was footed on gravel to save unexpected expense when the river alluvium turned out to be far deeper than anticipated. The pressure of the water impounded above the dam forced water down through the gravel under the dam and up on the other side, and in a short time a channel was scoured, the reservoir emptied, and the dam left hanging in the air. This dam likewise was constructed without a geological investigation.

A cavernous limestone was used as footing for the Hale's Bar dam on the Tennessee River near Chattanooga. This limestone extends downward for several hundred feet beneath the river bed. "On excavating for the dam foundation it was found that the limestone was honeycombed with intercommunicating solution channels, some of which were several feet in diameter and were choked with sand gravel, and cobbles, while others carried water under pressure. Excavation was carried some distance down into this rock and the foundation was thoroughly drilled and grouted, several hundred thousand barrels of cement being pumped into the openings. This honey combed foundation caused a delay of several years in the completion of the project and doubled or trebled the cost of construction.' [9] But even the the injection of several hundred thousand barrels of cement did not prove adequate to seal the foundation rock completely, for the cavernous condition continued downward to greater depths than were reached by the cement. About eleven years after the reservoir filled, leakage below the dam became serious. Efforts to stop it by dumping in rock, gravel, clay, mats, rags, burlap, carpets, cinder concrete, hay, wrecked bedsprings, and even corsets (elsewhere a firm foundation!) proved unavailing. Sufficient sealing was finally effected by drilling 68 holes to an average depth of 90 feet into the limestone below the dam and forcing over 11,000 barrels of hot asphalt down the holes and out into the openings in the rock. The presence of innumerable caves in this limestone was well known to geologists, and the dam would not have been footed on that formation had a geological investigation preceded construction.

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[8] Ransome, F. L. "Geology of the St. Francis Dam-site," Economic Geology, Vol. XXII, No 5, August, 1928, pp. 556-562.

Reservoir sites. "In considering the subject of geologic investigations in relation to proposed reservoirs it is well to distinguish between investigations of the dam site and investigations of the reservoir site. Geologic work on the dam site is restricted to a small area that is to contain the foundation and abutments of the dam, or perhaps to several small areas if there are several possible locations; but geologic work on the reservoir site must cover the much larger area over which the water is to be impounded."[10] From the standpoint of the geologist the entire problem of reservoir sites is whether or not the proposed basin will be practically water-tight. The answer lies in the permeability of the rocks forming the walls of the reservoir and the position of the water table in those rocks.

Soluble rocks, or those which have high porosity for other reasons are most likely to permit serious leakage. The most soluble rocks include limestone, dolomite, marble, and gypsum. In some places these rocks are already cavernous because of solution by ground water. Even where such rocks are not highly porous, they have potential porosity because of the possible dissolving action of reservoir water leaking through cracks and fissures. Basalt and other volcanic rocks may likewise be extremely permeable because of the presence of vesicles and other avenues for movement of water. Glacial drift and gravelly alluvium have high permeability and have been responsible for a number of reservoir failures.

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[9] Glenn, L. C., *op. cit.*, p. 108.

[10] Meinzer, O. E. *op. cit.*, p. 19.

> The pervious character of lateral and terminal moraines is worthy of comment as its dangers do not appear to have received the recognition that is due it. Large areas in the United States and Canada harbor seemingly admirable storage sites where nature has partly closed glaciated valleys by moraines, and where complete closure by means of inexpensive dams may readily be effected. Reservoirs so created, in a number of instances, have been disappointing because of uncontrollable leakage through the morainal deposits. In reporting some years ago on the condition of dams and reservoirs for the water supply of a Rocky Mountain city, the writer was surprised to find that out of seven reservoirs four leaked through moraines to so great an extent that they could not be filled to spillway level. Thus their most effective storage capacity was lost to the city. The dams were in excellent condition and showed no leakage, but water escaped over large areas through the reservoir bottoms and sides. Fortunately, in these instances the water was not completely lost, as it reappeared along the mountainside where it could be collected in pipes and so conveyed to the city, but it could not be completely controlled.[11]

Fortunately, there are many kinds of rock that are relatively water-tight and therefore satisfactory for reservoir walls.

> Types of rocks that seldom allow serious leakage from a reservoir comprise granite and other crystalline igneous rocks; gneiss, schist, slate, quartzite, and other varieties of metamorphic rock except marble; and shale, sandstone, and other fine-grained sedimentary rocks. These rocks may present a variety of serious problems at the dam and abutments, but only under exceptional conditions is there danger that they will allow serious leakage from other parts of the reservoir. Even a sandstone that yields water freely to wells will generally make a satisfactory containing rock for a reservoir, because the water will percolate through it too slowly to cause serious loss from the reservoir and because, on account of the slow movement of the water and the small size of the rock pores, the fine material carried in suspension by the surface water will be filtered out and will form an effectual seal.[12]

The position of the water table in the adjacent rocks with respect to the level of the water to be impounded is of utmost importance.

> Most large dams are built across the valleys of effluent[13] streams,

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[11] Matthes, Gerard H., *op. cit.*, p. 54.

[12] Meinzer, O. E., *op. cit.*, p. 22.

[13] An effluent stream is one that is receiving ground water from the sides of the valley.

> where the water table slopes toward the stream from both sides and appears along the banks of the stream in springs and seepage areas. If the water table ascends to a ground-water divide that is higher than the flow line of the proposed reservoir there will obviously not be any leakage, but ground water will continue to percolate toward the valley and will seep into the reservoir. . . . If in any direction from the reservoir site the ground-water divide is lower than the level of the proposed flow line it will form an underground spillway, over which the reservoir water will escape by percolating through the inclosing rocks. If the rocks are not very permeable the amount of water that will escape may be negligible, but if the rock is a cavernous limestone or a broken basalt the water may escape almost as freely as it would over a surface spillway. . . . The lower end of a reservoir is usually the most critical end. Here the water is impounded to the greatest height above the original stream level and is unavoidably raised far above the water table.[14]

Obviously, the proper geological evaluation of a reservoir site involves a detailed geological investigation. Because the water table is not only a fluctuating but also a rolling surface, its elevation at all parts of the basin and for all seasons of the year must be determined. A single place where the water table is depressed might become an underground spillway and not only permit serious leakage into an adjacent drainage basin, but also prevent filling of the reservoir. In addition to ground water studies, the surface and subsurface geology must be mapped in detail. The character of all of the formations composing the reservoir walls should be known, as well as pertinent structural information including the dip of the formations and the location, if present, of faults and shear zones.

The possibility that a reservoir may become filled with silt must be investigated by both the engineer and the geologist. The former, by means of a river-flow data and analyses of the water, can calculate the amount of silt now carried by the streams. The geologist by a critical examination of soil conditions in the drainage basin above the dam site can to some degree forecast possible changes in the amount of silt carried.

> Some power dams on the southern piedmont have been entirely filled and all reservoir capacity lost in two or three decades. Many others are partly full. Many of the irrigation reservoirs of the West are filling at a rate that will render them useless in 75 to 125 years. The Roosevelt, McMillan, Elephant Butte, and others show notable silting. The reservoir at Austin, Texas, has silted up more than 95 per cent in a little over a decade after it was rebuilt some years ago.

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[14] Meinzer, O. E., *op. cit.*, p. 23.

It is estimated that the Colorado River will fill the Boulder Dam reservoir in 190 years.[15]

Reservoir failures are not ordinarily as spectacular or disastrous as dam failures, but nevertheless may result in the complete abandonment of a project, with consequent financial loss. About 35 years ago the city of Seattle proposed to construct a dam across Cedar River in the Cascade Mountains in order to impound water for both power and municipal supply. A committee of geologists and engineers called in for consultation condemned the site, pointing out that one side of the proposed reservoir was a glacial moraine. Their report was ignored, and the dam was built. But before the reservoir filled completely, water suddenly broke out on the far side of the moraine, over a mile away and at an elevation 565 feet lower than the level of the water in the reservoir, and washed out a railroad grade, a sawmill, and a settlement. It is not only desirable to obtain geologic advice in engineering projects, but also to heed that advice.

> The Jerome reservoir, in Idaho, is situated in a depression underlain by several hundred feet of basalt flows. The water table is far below the surface, and leakage through the basalt, though the rock was protected by a cover of soil 10 feet thick in places, was so great as to cause the abandonment of the reservoir. The Hondo reservoir, in southeastern New Mexico, is situated in a natural depression surrounded by fairly substantial limestone. Below a surface soil the floor is underlain by shale and gypsum, as shown by drill holes, and according to the best information the water table lies about 200 feet below it. After the reservoir was constructed leakage through the cavernous rock beneath it was so rapid as to cause the formation of sinkholes in the soil, and the loss of water was so great that the reservoir was abandoned.[16]

Bridges. Bridge piers are footed on rock which must be adequate both to hold the great weight of concrete and steel and to resist the torsional pressure caused by the current pushing against the pier and tending to topple it. The foundation rock must also be resistant to physical and chemical erosion by the water flowing under the bridge. The foundations for the approaches also should be investigated to make sure that they can withstand the weight of the structure and fill. The fill itself must be composed of material that will not creep.

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[15] Glenn, L. C., *op. cit.*, p. 98.

[16] Bryan, Kirk, "Geology of reservoir dam sites, with a report on the Owyhee irrigation project, Oregon"; U. S. Geol. Survey, Water Supply Paper 597-A, 1929, p. 8.

A few years ago the State Geologist of Mississippi was requested by the highway department to pass upon the feasibility of erecting a bridge over the Yazoo River near Yazoo City. His report to the Mississippi State Highway Department, after describing the Tertiary and younger formations that make up the river bluffs, states:

> To an elevation of 131.7 feet above the flood plain . . . the bluff consists of clayey material which is most nearly impervious at the top where it is in contact with the overlying porous sand and gravel of the Citronelle, itself in contact with the overlying porous loess. The rainwater, transformed into groundwater, descends through the loess and thence through the sand and gravel until it reaches the clay which it cannot penetrate. Consequently, it must flow along this clay contact until it reaches the valley side, which intersects the contact plain. Here the water issues as seeps and springs. Accordingly, it not only adds its weight to the mass, already in an unstable condition of equilibrium, but also lubricates the underlying clays, making them plastic and extremely slippery. Such contacts of underlying impervious clays and overlying porous beds always result in landslides, and the bluffs at Yazoo City are no exception to this rule. As a matter of fact some of the loess has already slipped away to the very top of the bluff 245 feet above the valley flat, which developed a crack in the northwest corner of the concrete lined and capped city reservoir, that permitted its waters to pour forth in a roaring torrent—resulting in its abandonment.
>
> For a half mile or for even a mile, therefore, the eastern highway approach to a bridge at this site would have to be constructed over a terrace that, in most places, has slipped in the past; that, in some places, is still slipping up to the present moment; and that, in most or all places, will continue to slip for an indefinite period, or until a state of equilibrium is reached in the untold ages of the future. To dump material for a highway fill upon any of the four sides of these two spur ridges, the westernmost side of the western of which is the Yazoo Bluff itself, would simply be to add to this unstable condition. Undoubtedly it would hasten the initiation of the slipping which would inevitably follow. To remove any of this unstable material and any additional stable material beneath would also disturb the present temporary equilibrium and would also hasten the initiation of slipping. Even though the east pier of the bridge at this site could be seated in the bed rock of clayey, calcareous marl, the construction of fills and the excavation of cuts would initiate sliding of such magnitude as to threaten the pier, as to dissipate the fills, and as to fill the cuts. Hundreds and hundreds of tons of landslide material would have to be removed at intervals for years to come, even if the pier itself were not thrown out of alignment by the impact. In short, to construct a main thoroughfare approach to the

bridge at this site is simply to invite disaster. It is an impossible location.[17]

By acting upon the recommendations in this report the State in all probability saved many thousands of dollars.

Tunnels. Tunneling through rock is a very expensive operation, and the magnitude of the expense is dependent largely upon the kind of rock encountered. Rocks such as granite, quartzite, and basalt are very hard and tough. Tunnels can be driven through most sandstones and shales at much less expense. However, if the rock is too loose it will cave, and there wlll be the added cost of holding up the roof as tunneling progresses. The structure of the rocks is important because of the effect it may have in bringing different formations across the line of the projected tunnel and because of the control it has on the distribution of ground water. The rock sequence anticipated in driving the tunnel will indicate where large flows of water may be expected, so that precautions for adequate drainage can be made in advance.

All faults should be discovered and mapped in advance if possible, for not only may they cause an abrupt change in the character of the rock, but they may be bordered by a zone of sheared rock with caving tendencies. In addition, careful observation should be made of faults to see whether they are "alive" or "dead." If there is any evidence whatsoever of recent movement along the fault plane, the tunnel site should be condemned.

A geological investigation of a proposed tunnel site calls for very accurate and detailed mapping of the surface geology through exposures above the tunnel and in nearby valleys. The downward and inward trend of the different rocks should be determined by strike and dip readings. If the rocks are bedded and without angular unconformities this is a fairly simple procedure. However, if the rocks are igneous or metamorphic, unforeseen changes may take place in the trends, and diamond drilling under the direction of a geologist should precede the driving of the tunnel. Detailed geological studies may lead to the discovery of other possible tunnel sites in which costs would be materially less.

A complete geological report was not prepared before the driving of the Moffat tunnel through the Front Range of the Rockies above

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[17] Morse, W. C., Geologic Conditions Governing Sites of Bridges and other Structures, Mississippi State Geological Survey, Bulletin 27, 1935, pp. 12-14. Published by the University of Mississippi.

Denver. During the construction of the tunnel a series of shear zones was encountered in which caving of such magnitude occurred as to both delay completion many months and enormously increase the expense. An illustration has been cited[18] of a railroad tunnel which was driven through a mountain ridge in Pennsylvania, but which bankrupted the contractors. The ridge happened to be an anticline with soft shale exposed at both the portal sites of the projected tunnel and across the top of the hill between. The contractors, not being geologists, failed to recognize the anticlinal character of the rocks and assumed that the shale extended clear through the ridge. However, they soon found that the shale was arched up and underlain by a very hard sandstone through which most of the tunnel had to be driven.

Highway construction. The modern highway is constructed with a minimum of grades; the hills are cut and the hollows filled. Road cuts made through solid rock are very expensive. A geological investigation of a hill in which a cut is anticipated will result in an accurate forecast as to both the quantity and kind of rock that will be encountered. These data can be used in estimating cost, and if it is excessive, the geologist may be able to recommend an alternative and much less expensive routing.

Slides from the walls of cuts and adjacent hillsides are a recurring item of expense to highway departments. A geological study leads to the recognition of rock types and structures favorable to sliding. Where such rock is encountered and recognized, it may be possible either to avoid this rock altogether by a slight change in routing or to plan the cut so that the slopes will be less than the angle of repose of the material.

Landslides may cause difficulty not only in highway building, but also in railroad, dam, aqueduct, and other construction projects involving excavation. Except for very small slides, retaining walls are ineffective. Most control efforts can be classified under one of three headings: (1) treatment of unstable slopes, (2) consolidation of the unstable material, and (3) correction of the ground water conditions which cause the lubrication of the material tending to slide. One method of slope treatment, decreasing the angle of slope, was mentioned in the preceding paragraph. This merely does what the side was attempting to do. Another common procedure for increasing the stability of creeping earth slopes is to grow deep-rooting plants on the surface. These serve the dual purpose of increasing soil stability with their network of roots and of extracting water from the mantle.

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[18] Agar, W. M., Flint, R. F., and Longwell, C. R. *Geology from Original Sources,* p. 478. New York: Henry Holt & Company, Inc., 1929.

Consolidation of the unstable material has been accomplished by grouting with cement and by freezing the sliding mud. The latter method is obviously temporary, but it does permit the uninterrupted completion of foundations. It was used most successfully during the construction of the Grand Coulee Dam in Washington.

Ground water drainage to stop sliding has been successfully employed in several places. The common procedure is to lower the water table in the vicinity by diversion of surface drainage, pumped wells, and even by tunnels. One sliding area in California was brought under control by forcing warm air through a series of tunnels into the clay mass in order to dry it out.

Still another problem in highway construction is the strength and permanence of foundations and fill. It is necessary, of course, in most instances to utilize whatever material is available. Fills are made of the material either moved from adjacent cuts or lying alongside the grade. However, some rocks, particularly certain clays, will not hold a concrete slab without sliding. Other types of road material soak up instead of draining water, and so alternately swell and shrink depending upon the climatic conditions. In these cases it is advisable to discard local material and to construct the grade with rock brought from a greater distance.

Recently, geologists have been utilized by highway engineering staffs to determine the direction of flow of water underground. If the direction of the established subsurface drainage is known, it is possible to place the highway drains where they will do the most good. Formerly the drains were indiscriminately placed on both sides and through the grade, resulting in much unnecessary expense.[19]

Military use of geology. The peace-time duties of the United States Army Engineers include supervision of such public works projects as flood control, including the construction of dams impounding great reservoirs, and harbor development. Both consulting engineering geologists of recognized ability and resident geologists are employed on the larger projects.

It was not fully realized at the start of the first World War that geologists could be of assistance even on the battlefield. The few geologists who were attached to the general staffs of the different armies had much prejudice to overcome in regard to their value in active service, and they were in a position to observe the many mistakes brought on by lack of utilization of geological advice. The following paragraphs are quoted to illustrate the value, or at least the potential value, of applying geology to war-time activities of an army in the field during World War I:

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[19] Hilton, Willard Q., Geologist, Kansas Highway Commission: *Informal Report*, 1938.

> During the great battle of Verdun a body of troops was ordered to intrench itself on the high plateau of the Côtes de Meuse. Even a casual examination of the geologic map would have shown that the plateau was underlain by hard limestone with less than a foot of soil. This material could not be excavated with the light tools furnished or even with proper equipment in the time available. As a consequence there was a large and needless loss of life. . . .
>
> In the early part of the war, when transportation facilities were crowded to the limit, the British brought road metal from England in ignorance of the fact that a geologist was able to designate readily accessible sources in the theater of operations. A responsible officer in our own service made a requisition for filter sand to be transported across the Atlantic, though the geologists of the American Expeditionary Force had already found localities where such sand could be procured in France. . . .
>
> In our Army many large plants, such as hospitals and flying fields, were located without any definite knowledge of the source of needed water. In the British Army, after the first year, no well drilling was permitted without the approval of the geologist in charge of water-resource investigations. There was no such rule in the American Expeditionary Force, and many wells were drilled with no adequate knowledge of the underground-water conditions. In many instances it was not until hospitals or other large plants actually had a shortage of water that the geologist was called into consultation.[20]

> The hazards of war do not always permit an army to select the terrain on which it will fight. Nevertheless it is evident that in a region like the Somme the terrain on which battle is delivered may be intelligently or unintelligently utilized. Unfortunately it happened during the great war that a higher officer, even a general of engineers, would sometimes remain blindly unaware of the vital relation of geological structure to the fighting power of his army, while his subordinates complained bitterly of the wasted effort and the unnecessary suffering which such ignorance entailed. Dugouts were excavated and then found useless because it was impossible to drain them. Tunnels and mines driven at great cost of time and labor were abandoned before attaining their object, because a water-

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[20] Brooks, A. H., The Use of Geology on the Western Front, U. S. Geol. Survey, Professional Paper 128-D, 1920, pp. 87-105.

> bearing zone above or below was cut into and the workmen "drowned out." Men suffered misery in trenches deep with mud and water. And all this when changes of but a few feet in surface location or differences of a few feet in depth of excavation, perfectly feasible from the tactical point of view, would have avoided the damage incurred. Even with no change of location, drainage could often be effected by sinking in the bottom of the wet trench or dugout a narrow subsidiary trench reaching into an underlying pervious formation, or by driving pits or wells down into that formation so as to let accumulated waters escape below. With the lapse of time and at the cost of bitter experience these facts became more and more widely known.[21]

The start of World War II found the American military organizations no better prepared to utilize geology than they had been at the beginning of World War I. This condition existed in spite of the widely known fact that the German army organization included geologists on the staffs at all levels. According to the fairly voluminous pre-war literature produced by German military geologists, the duties of the general staff geologists and geographers were to guide war mineral exploration and exploitation in Germany and acquired territories, while the specialists attached to the field armies were to advise the combat units concerning terrain, water supplies, construction materials, and allied subjects. It was reported that the German Wehrmacht included no less than 600 geologists in the Italian and North African campaigns alone.

Fortunately, during the spring of 1942, the U. S. Corps of Engineers became aware of the latent possibilities in military geology, and liason was established with the U. S. Geological Survey which led to the establishment of a Military Geology unit in the latter organization. Some of the accomplishments of this group have been interestingly described by Saturday Evening Post writer Martin Sommers, from whose article the following random paragraphs are quoted:

> This is to report on one of the most interesting and important additions to the collective brain of the United States Army. It was sired by the Army's Corps of Engineers, out of the United States Department of the Interior. An enthusiastic engineer officer once called it "our Civilian Task Force No. 1." It consists of a unit of around 100 of the ablest geologists—fourteen of them women—this country could mobilize, and their assistants. Today, in the catacombs of one of Washington's older office piles, they labor night and

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[21] Johnson, Douglas W., *Battlefields of the World War.* American Geographical Society, Research Series No. 3, 1921, pp. 117-119.

day at a monumental task of scientific fortunetelling—the preparation of detailed reports which, in advance, tell our assault troops the kind of terrain and subterrain they will find when they strike at objectives from China to the Ruhr, and from Attu to Luzon. In addition, civilian combat teams are chosen from the more rugged members of the unit and sent out to the battlegrounds to analyze the terrain on the scene, and to check on the accuracy of the office-brewed reports, so that this type of military intelligence can be improved for future operations.

Here is the broad word picture of what this civilian task force does: Working from a topographical map, which presents the surface features of an area, and a geological map, a multicolored mirror of what lies beneath the surface, the scientists tell the Army where to find the best sites for airfields, water, soil suitable for road building, stone for cement, other construction materials, and just about anything else the military planners may desire. In 1942, the geologists proved that, lacking air photos, they could take those two simple weapons, the topographical map and the geological map, and, from their knowledge of their science, produce thirteen volumes of information, including about 1,000,000 useful facts, on North Africa. Air photos on North Africa were not obtainable until September, 1942, too late for much of the advanced planning for the early November invasion that year.

Long before the marines hit the beach on Guadalcanal, the Air Forces wanted the geologists, then just getting started in Washington, to suggest the best possible areas for an airfield site on the island. The scientists had no real information—a few odd photographs of dubious value and snatches of comment from missionaries, made long in the past, constituted the whole. But they went to work at imagining what the soil and water conditions would be like, basing their frank guesses on data about other islands thought to be similar to the Solomons geologically. One deduction was checked against another until the process became something like a debate. Finally, a site was recommended. It turned out to include what is now Henderson Field. The military expressed ungrudging admiration for a guess made on the basis of no intelligence, at a range of 10,000 miles.

The range of the uses to which the geologists' scientific divinings can be put seems endless, judging by reports which have come back from the global fronts. In Sicily, American lines were being bombed by planes from a hidden German airfield. Our planes couldn't find it. As a last resort, air intelligence officers turned to the folio that had been prepared for the Sicilian invasion, with possible airfield sites neatly indicated. After they checked known fields against possible sites, the Luftwaffe hide-out was located and blasted out of action.

When Maj. Gen. Claire Chennault's 14th Air Force first was

> established in China, targets had to be very carefully selected because the supply of planes, bombs and fuel was limited. The air strategists wanted to make certain that when they attacked important Jap mining installations they would be sure to hit the buildings most vital to the production of refined ore. Some of the geologists are world-renowned specialists on ore deposits. They were able to pin-point targets, notably the Fusan installations, the zinc smelters at Haiphong, and the Celebes nickel mines.[22]

In addition to those connected with the Military Geology section of the U. S. Geological Survey, hundreds of civilian geologists were in other governmental branches, and in private industry, engaged in a relentless search for new supplies of strategic minerals, not only in the United States, but also in Canada and Latin America. That this activity was successful is attested by the fact that no war production or allied military campaign was held up for any length of time due to lack of mineral raw material.

Geologists in service were utilized to some extent in prospecting for ground water supplies and as interpreters of terrain from air photos.

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Geology in the post-war world. The cessation of hostilities in 1945 did not produce a lessening in the use of, or demand for, geologists. On the contrary, the peoples of a bomb-frightened world demanded that the search for radioactive ores and other strategic minerals be not only continued but accelerated. The authorities in this country, and no doubt elsewhere, have made a survey (in which geologists assisted) of all underground openings such as natural caves and man-made mine workings as possible sites for essential industries in future "emergencies." Every country, and especially the United States, drew heavily upon mineral reserves during the war years, and a vigorous prospecting campaign is under way in an attempt to discover new supplies adequate to take care of normal peace-time domestic demand.

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[22] Sommers, Martin, "The Army's Pet Prophets," *The Saturday Evening Post,* March 24, 1945. Reprinted by permission of the Curtis Publishing Company.

The utilitarian value of geology has been amply demonstrated; the challenge that now faces the science is that of obtaining equal success in demonstrating its cultural values.

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